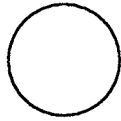


**Gesellschaft für
Reaktorsicherheit (GRS) mbH**

**Konrad Transport Study:
Safety Analysis of the Transportation
of Radioactive Waste
to the Konrad Waste Disposal Site**

F. Lange, D. Gründler, G. Schwarz

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ABSTRACT

A safety analysis has been conducted for the transports of non-heat-generating (low-to medium-level) radioactive waste to the planned final repository KONRAD. The safety analysis has two main objectives:

- 1) Assessment of potential radiation exposures from normal (incident-free) transportation, especially in the region of the final repository where all waste transports converge.
- 2) Assessment of risks from transport accidents in the region of the final repository, i.e., the quantification of the frequency of accidents and of possibly resulting radiation exposures and contamination levels.

For the purpose of the study the anticipated waste transport volume and the waste properties were analysed in detail. This included information on the transport containers, waste product properties, activity inventories and local dose rates of the waste packages being transported. The envisaged practical implementation, i.e. the transport arrangements including shunting operations at the Braunschweig marshalling yard and the Beddingen interchange station, were also included.

Two shipping scenarios, which could be considered to bound the real conditions, were analyzed:

- 100 % transportation by rail
- 80 % transportation by rail, 20 % by road

The relevant transport regulations contain the requirements to be met by the transport of shipping units carrying radioactive waste. In addition, the "KONRAD preliminary waste acceptance criteria" contain activity limits for waste packages being disposed of in conjunction with further requirements relating to the properties of waste products and waste containers. These regulations and acceptance criteria represent the framework of the safety requirements for the waste packages. However, they do not provide any information on the type, quantity and properties of the radioactive waste actually produced and requiring disposal. Consequently, the availability of an extensive and detailed waste data survey of the Federal Office for Radiation

Protection (BfS) was of fundamental importance to the safety analysis. Completed in summer 1990, a nation-wide survey was conducted with the aim of obtaining comprehensive data on the radioactive waste produced and to be anticipated in the foreseeable future in the Federal Republic of Germany (not including the five new federal states). These data refer in particular to the activity contents of waste packages and the local dose rates derived from these. Overall, the waste volume is characterized by 217 reference waste types and the related average annual quantity produced.

On the basis of the surveys and analyses conducted annually by BfS with respect to the existing waste volume, the additional new waste produced and the expected waste volume for the immediate future, the final repository KONRAD will probably be operated on a single-shift basis. This would result in the transportation of about 3,400 shipping units annually.

If it is assumed that radioactive waste from the five new federal states will also be delivered to the KONRAD waste disposal site when it is in operation, such a supposition is not expected to significantly influence the results of the present study:

- The current waste volume is comparatively small. Based on many years' data, approximately 200 shipping units were transported per year to the Morsleben waste repository formerly operated in the GDR.
- The activity contents and concentrations of the remaining waste can reasonably be expected to be on a scale similar to that of the waste occurring in the Federal Republic of Germany before the accession of the GDR, and at any rate must satisfy the waste acceptance requirements of the KONRAD waste repository.

Radiation Exposure from Normal Transport

The total annual radiation dose received by an individual as a result of waste transports passing by or halting in its vicinity is derived from the local dose rate at each location and the cumulative period of time spent by individuals at these locations during a period of one year. In this context, the study concentrated on exposure situations in which groups of persons are particularly exposed to the radiation field of the waste packages as a result of their living habits or their occupation. This corresponds to the normal procedure adopted in radiological protection in order to

determine the potential doses to "critical groups of individuals". For persons who do not belong to the "critical group", the radiation exposure caused by the waste transport can generally be expected to be lower, and in most cases much lower, than for those in the critical group.

General population

The doses determined for critical group individuals of the population in the region of the final repository range approximately from 0,02 to 0,1 mSv/a. To a large extent, doses are in the lower range of 0,02 mSv. This is either because on an average only short periods of time are spent in the immediate vicinity of the waste transports, since the vehicles generally pass by or halt only for a short time, or because of the larger distances between the individual and the waste transports. Less favourable conditions with respect to duration of exposure and spatial distance can lead to radiation exposures above 0.02 mSv. The highest exposure conditions were determined for residents of buildings directly adjacent to the Braunschweig marshalling yard in the Alte Salzdahlumer Strasse area. They are relatively close to goods trains with waste wagons parked on tracks in the reception sidings; the longer standing times inevitably lead to longer periods of exposure. These circumstances represent an exceptional local situation which exists only here and not at any other locations either in the Braunschweig marshalling yard or in the region of the final repository. In the case of the 80 % rail/20 % road transportation scenario, the effective doses are up to 0.1 mSv/a for the critical group in the Alte Salzdahlumer Strasse area. In the extreme case of 100 % rail transport and assuming that all regular goods trains are routed via the Braunschweig marshalling yard, the annual radiation exposure of this group of persons can reach values of up to 0,2 mSv/a.

The potential radiation exposure of critical groups of persons in the population as a result of waste transports is well below the value of 1 mSv/a recommended by the IAEA transport regulations. To permit a clearer understanding of the significance of the annual radiation doses determined for the critical groups of persons, they can be compared to natural radiation exposure applicable to all persons. In the Federal Republic of Germany this has an average value of about 2 mSv/a, although the exposure varies in a wide range dependent on the place of residence and other personal circumstances. The additional radiation exposure of the critical groups of

persons as a result of the waste transports is equivalent at the most to a small fraction of natural radiation exposure. The radiation exposure of these groups of persons, and consequently even more significantly of those inhabitants of the region around the final repository who do not belong to the relatively few individuals of the critical groups, remains practically unchanged by the waste transports.

Transport and handling personnel

Considering the persons who are occupationally involved with waste transportation, that is employees of the Federal German Railways and Verkehrsbetriebe Peine-Salzgitter, the dispatch and marshalling personnel at the Braunschweig marshalling yard and Beddingen interchange station, who are primarily involved in shunting and dispatching the waste wagons must be regarded as the critical group of persons. Depending on their functions, maximum doses of approximately 0,3 - 0,7 mSv/a are obtained for the small number of persons making up this group. For the other marshalling personnel, doses are significantly lower.

The radiation exposure of the dispatch and marshalling personnel involved in the waste transportation is in a dose range that has also been observed in some cases in other railway areas with a high volume of radioactive consignments. The values determined are significantly below the dose limit of 5 mSv/a applicable to this group of persons.

Transport Accident Risk

The risk of transport accidents is determined by the frequency of accidents leading to a release of radioactive substances and the potential radiological consequences, such as radiation exposure of persons and contamination of the biosphere. To assess the risk associated with transport accidents, the region in the proximity of the final repository KONRAD is considered and this is defined as the area within a radius of 25 km around the installation. This region, for which the accident risk of the entire waste transport is calculated, is chosen since it covers all waste transports converging in the vicinity of the final repository and the rail and road transport routes representative for this region. This includes the Braunschweig

marshalling yard, through which a large proportion of the waste transport is expected to be routed.

The frequency and magnitude of the radiological consequences for the waste transport volume depends on several parameters including especially:

- the frequencies with which accident loads affect waste packages,
- the properties of the waste containers and the waste product contained which determine the release behaviour,
- the content of radioactive substances (activity inventory),
- the frequency of occurrence of different atmospheric dispersion conditions; these can influence the airborne and deposited contaminant concentrations and thus, to a large extent, the radiological consequences.

To take these parameters into account, possible accident loads of transport vehicles and transport containers were divided into 9 severity categories; the associated relative probabilities of occurrence were determined by evaluating accident statistics for railway goods traffic, heavy goods vehicle traffic and the Braunschweig marshalling yard. Because of the wide ranging differences in the behaviour of the various container types (concrete, cast iron and steel plate containers) and, where applicable, of the different waste products (e.g. cement/concrete, bitumen), under accident loads, the transport volume was broken down into various waste container groups. For this classification, the release behaviour is the deciding criterion. The fraction of the activity inventory assumed to be released from waste containers was then determined for each of the pre-defined severity categories and waste container groups. The activity inventory of shipping units affected by an accident then determines the released activities of individual radionuclides, the source term.

The potential radiological accidental consequences, such as radiation exposure of persons and contamination of soil and vegetation, are calculated using the UFOMOD accident consequence program.

In calculating radiation exposure, the following exposure paths are taken into account:

- cloudshine
- groundshine (70 yrs)
- inhalation (intake of activity with respiratory air)
- ingestion (intake of activity with food , 70 yrs)
- resuspension (reentry of radionuclides deposited on the ground into the air) with subsequent inhalation (70 yrs)

The calculations take into account the relative frequency of the atmospheric dispersion conditions in the region of the final repository. For this, the weather data of the German Meteorological Service (DWD), Offenbach, collected at the Braunschweig-Völkenrode weather station, situated north-west of the Braunschweig municipal area, were available.

An accident simulation program was used in order to cover the spectrum of possible accident sequences including the releases of radioactive substances and the anticipated frequency of the events. This program considers the transport volume under investigation (217 types of reference waste and their relative frequency), different transport constellations, such as the number of waste wagons in the goods train and their consignment, and possible accident loads (9 severity categories). Based on this, a large number of source terms is generated, which are representative of the possible releases of radionuclides caused by accidents. The program simultaneously records the frequency of occurrence of such releases.

In a further step the large number of generated source terms are ranked by increasing radiological importance and then subdivided into 10 source term groups. By taking into account the conditional probabilities of the individual source terms belonging to a source term group a representative weighted source term - a so-called release category - is determined for each source term group. These release categories are representative with respect to the radionuclide composition and the released activities of individual radionuclides for calculating the radiological consequences. Ten such release categories each have been generated by the simulation program for accidents during transportation by goods train, by truck, and in the Braunschweig marshalling yard. In each case 5 release categories are representative for accidents with purely mechanical impact on shipping units,

and 5 release categories 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 waste transports for one year, this is the probability with which releases caused by accidents, which are represented by a release category, can be expected in the region of the final repository.

In conducting the analysis of the accident risk, the model parameter values were generally specified in a conservative manner. This refers in particular to the definition of the severity categories, the assignment of accident events to severity categories, and the derivation of the frequency with which accidents in a specific load category occur. The combination of these conservative assumptions in the context of the accident risk analysis results in the clear overestimation of both the estimated frequencies of accidents as well as, to a large extent, the amount of activity release (source term).

The results of the probabilistic risk analysis of transport accidents in the region of the final repository are expressed as cumulative complementary frequency distributions for three transport operations:

- waste transport exclusively with goods trains (100 % rail)
- waste transport partly with goods trains and partly with trucks (80 % rail/20 % road) and
- at the Braunschweig marshalling yard.

The frequency distributions are obtained by superimposing the results of each of the ten release categories. The frequency distribution thus obtained represent the frequencies of occurrence of the release categories resulting from transport accidents within the 25 km radius.

The frequencies of specific radiological consequences in the region of the final repository as a result of transport accidents can be obtained from the complementary frequency distribution curves. In this context, the radiological consequences are represented in different ways:

- as radiation exposure in the form of effective doses in the immediate vicinity of an accident location in the direction of dispersion of the contaminant

- as Cs 137-equivalent soil contamination. This is to enable a comparison with the Cs 137-fallout in the Federal Republic of Germany as a result of nuclear weapons testing and the reactor accident in Chernobyl.

In calculating the potential radiation exposure levels, it is assumed that no countermeasures are taken at distances beyond 250 m from the accident location; this is especially with respect to the post-accident removal of radioactive substances deposited on vegetation and other surfaces or other measures to reduce possible radiation exposure. However, for illustrative purposes, separate calculations were carried out for shorter distances and for a distance of 250 m from the accident location in which only the potential radiation exposure through inhalation is determined. This permits a comparison for obtaining the contribution of the long-term exposure paths groundshine, ingestion and resuspension to the total dose. This indicates the extent to which post-accident measures can contribute to reducing radiation exposure.

The cumulative complementary frequency distribution curves show the expected frequencies of radiological consequences from transport accidents in the region of the final repository. The expected frequencies are for the area around the final repository within a radius of 25 km, that is, the frequencies per year of such events anywhere within this area.

CONCLUSIONS

The results of the transport risk analysis can be summarized as follows:

- It is unlikely that transport accidents with a release of radioactive substances will occur in the region of the final repository during the operating period of approximately 40 years.
- Because of the lower accident risk of transports by rail as compared to road, the envisaged high fraction of rail transport of the entire transport volume has a beneficial effect.
- In case of an accident with release of radioactive substances, the potential radiological consequences decrease rapidly with distance; starting from around 250 m by a factor of 10 up to about 1,200 m and a further factor of 10 at a distance of about 6,200 m.

- The releases associated with accidents are frequently so small that the potential radiation exposure even without countermeasures is below the natural radiation exposure for one year, at a distance of about 250 m from the accident location, this is true for 9 out of 10 accidents with goods trains and 19 out of 20 accidents with trucks.
- With the hypothetical assumption of a continuous operation of the repository, a potential effective dose of 50 mSv without countermeasures would result on an average once every 500 000 years at a distance of 250 m in the direction of atmospheric dispersion for the scenario 100 % rail transport and once every 400,000 years for the scenario 80 % rail/20 % road. 50 mSv corresponds to the design guideline exposure of § 28 Para. 3 of the German Radiological Protection Ordinance and the annual dose limit for persons occupationally exposed to radiation.
- The expected frequencies of corresponding accident consequences are considerably lower for the Braunschweig marshalling yard.

The above-mentioned frequencies of possible accident consequences are the result of the transport risk analysis. It should be noted in this context that these values are definitely overestimated because of the interaction of conservative assumptions made in the framework of the analysis. It can thus be concluded that the waste transports do not pose any major additional risk to the region of the repository. The individual risk from a transport accident for a person living close to a transport route is even smaller. The reasons for this include:

- An accident would have to occur within the vicinity of the place in which an individual is located. Even if the route concerned is a stretch on which accidents are more likely to occur, the likelihood of an accident is clearly lower than for the entire region around the repository.
- In general not all transports will be routed via this section of the route, since alternative transport routes are available.
- To be affected, the person would have to be situated in the direction of atmospheric dispersion from the accident site, the probability of which is also lower.

Overall, the results of the transport study show that no major associated risks would result from the converging waste transports destined for the final repository KONRAD for the region around the site. This applies to both normal transport and transport accidents.

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1 Principles and Objectives

Like all activities in our civilized world the transportation of radioactive waste on public routes or routes to which the public has access (e.g. rail/road) entails some elements of risk - nuclear and nonnuclear - for man and his environment. The risks involved in waste transportation comprise the radiation exposure of the population and transport personnel from normal, accident-free transportation, as well as from possible transportation or handling accidents with the potential of causing radiation exposure of people and contamination of the surrounding area.

The Federal Minister for the Environment, Nature Conservation and Reactor Safety (BMU), Bonn, commissioned the Gesellschaft für Reaktorsicherheit (GRS) mbH, Cologne, to conduct a study that examines this situation more closely. Its objective is to quantify the type and extent of the risks associated with waste transportation to the KONRAD waste disposal site. The KONRAD site is a disused iron ore mine within the city boundaries of Salzgitter in the south of Lower Saxony designated for the disposal of waste with negligible heat generation. Independent of the plant-specific licencing procedure for the Konrad waste repository, the present study is intended to make a further contribution to the safety evaluation of the entire subject area.

In addition, however, the study is prompted by public concern expressed in the region of the waste disposal site indicating that the anticipated waste transportation constitutes an undue risk of personal safety and therefore a potential danger for man and his environment. In this respect the present study also represents an attempt to establish a sound scientific basis for the public debate on the problems of transportation, in particular in the region of the KONRAD waste repository.

The transport of waste to the disposal site is subject to regulations on the transportation of dangerous goods, in particular as stipulated in the Directive on the Transportation of Dangerous Goods by Road (GGVS) /GGS 90/ and the Directive on the Transportation of Dangerous Goods by Rail (GGVE) /GGE 85/. The transport regulations provide for the properties of different types of dangerous goods by distinguishing between various hazard categories. The provisions governing the transportation of radioactive materials (Hazard Category 7) are based on the "Regulations for the Safe Transport of Radioactive Material" published and continuously updated by the International Atomic Energy Agency (IAEA) /IAE 85/. The regulations embody the require-

ments which transports of consignments containing radioactive material must satisfy. As far as the packaging requirements are concerned a graduated safety system applies; the requirements packagings must satisfy become more stringent as the activity content increases along with other properties of the radioactive material relevant for a possible release and culminate in Type B packages which must be capable of withstanding extreme mechanical or fire-related accidental forces.

The conduct of a safety analysis considering the potential radiological consequences from normal transportation and for potential accidents for a specific transport volume, albeit one that is perhaps only anticipated for the future, satisfies the recommendations of IAEA transport regulations /IAE 85/. According to § 203, the competent authority is required to have periodic assessments carried out in order to determine the radiation exposure to which transport personnel and the population could be subject to as a result of the transportation of radioactive materials and, in particular, also to investigate whether the necessary measures have been taken to ensure by appropriate means that radiation exposure is kept as low as reasonably achievable. A feature that distinguishes waste transports to the planned KONRAD waste disposal site is that the transports are concentrating in the region of the waste disposal site. The study must therefore investigate whether a significant additional risk could arise in this region for the population or transport personnel from normal transportation or from accidents. Consequently, the present transport study focuses on potential consequences within a radius of 25 km of the waste disposal site.

The report starts by presenting the general procedure and the database. The methods applied are described in greater detail in Appendices (separate Volume) in order to explain the basic ideas for the study. The following questions relating to the transportation of waste are of particular interest for the study and are examined in depth:

1. What types and quantities of radioactive waste are provided for transportation?
2. What are the radiologically relevant characteristics of the waste packages, i.e. the radioactive inventory and the local dose rate?
3. Which conveyances are used and on which routes?
4. How great is the additional traffic volume?

5. What is the type and extent of the potential radiological consequences from normal (accident-free) transportation?
6. What is the type and extent of the potential radiological consequences in the event of transportation accidents, and at which frequency do such accidents occur?

The basic results of the study are presented as potential radiation doses expressed as effective dose (weighted whole-body dose). Radiation exposures arising from normal transportation are stated as individual doses and collective doses. Individual doses refer to groups of people who may specifically be affected by waste transportation as a result either of their circumstances or their profession. Natural radiation exposure and the dose levels embodied in the transport regulations are applied as comparative variables. Collective doses state the total radiation doses for a population of people, e.g. residents along transport routes or transport personnel. The natural radiation exposure of the population under examination is taken as the comparative variable.

The findings on the accident risk are represented in graphs where potential radiation exposure is plotted versus the anticipated frequencies of occurrence. The graphs show the relationship between potential radiation dose as the result of an accident and the frequency with which such effects can be anticipated for the waste transport volume under consideration. The natural radiation exposure and an effective dose of 50 mSv are used for comparison. 50 mSv corresponds to the dose level specified in § 28, Sect. 3 of the Radiation Protection Ordinance for nuclear power stations and other installations which are subject to the licencing procedure according to § 7 of the German Atomic Energy Law (AtG) and the dose limit per calendar year for persons occupationally exposed to radiation.

2 Description of Methods

The subject of investigation of this study encompasses the determination of potential radiological consequences from normal (accident-free) waste transportation and the transport accident risk.

The present investigation is based on the developmental stage as of autumn 1990 of the planning and licencing documents for the KONRAD repository. This applies in particular to:

- the intended waste and transport containers
- the local dose rates and radioactivity inventories of the waste packages
- planned sequence of the storage operations.

The conditions and arrangements for a typical transportation operation from the customer to the waste disposal site were determined and prescribed in close cooperation with relevant transport enterprises and other companies. These include specifically the German Federal Railways (Deutsche Bundesbahn - DB) and the Verkehrsbetriebe Peine-Salzgitter (VPS).

For the purpose of the study it was assumed that all the relevant regulations governing the transportation of radioactive materials apply without restriction and are complied with. This refers specifically to the local dose rates for the packages stipulated in the Directive on the Transportation of Dangerous Goods by Rail (GGVE) and the Directive on the Transportation of Dangerous Goods by Road (GGVS) as well as the provisions applicable for the general public and the transport personnel.

2.1 Normal Transportation Operations

The radiation exposure associated with normal, accident-free transportation can be attributed to the fact that people who find themselves regularly or by chance in the direct vicinity of passing or stationary vehicles carrying waste, or who are professionally required to work with such, e.g. marshalling personnel, may be exposed to the field of radiation emanating from the waste containers. Assessment of potential exposure situation (e.g. duration, type and magnitude of the radiation field) and the determination of the resultant radiation exposure - whether in the form of individual or collective doses - is one of the central objectives of the present investigation. The annual radiation dose of individuals is then derived from the local dose rate at the places where the people receive exposure and the total time they spend in these places in the course of a year.

As regards estimating the individual dose note that the most relevant of the large number of possible exposure situations are those in which individuals or groups of people receive especially high exposure from the radiation field of the waste packages owing to their circumstances or profession. In this respect the study concentrates on estimating the potential doses of these individuals or groups of people who are also described as "critical groups". This is consistent with a procedure widely used in radiation protection. Individuals not belonging to the critical groups can thus be expected to be exposed less, or generally very much less, to radiation as a result of waste transportation than those in the critical group.

2.2 Transport Accidents

Analyses of transport accidents or transport risks are generally conducted with the objective of quantifying accident situations as regards their course of action, consequences and probability of occurrence. In doing so, accident sequences must also be included in which the mechanical and/or thermal impact limits of the transport packages envisaged by the design are exceeded and a package failure may result.

The requirements which must be satisfied by the container design, the form taken by the radioactive materials it contains and the permitted activity content are defined in the following regulations:

- The transport regulations /GGS 90, GGE 85/ based on the IAEA Regulations for the Safe Transport of Radioactive Material /IAE 85/
- The "Provisional Waste Acceptance Requirements" /BFS 90/ derived from the safety analyses for the planned KONRAD waste repository.

The waste packages must satisfy both these stipulations which, despite certain differences in the requirements derived from the theoretical models are based on a comparable safety concept: Possible radiological impact should be avoided or minimized also in the event of transport accidents involving severe impacts or incidents at the waste disposal site. To make this possible, the permitted activity content of transport containers is limited depending on the container properties and the form which the radioactive substances take. Vital importance is attached in this connection to minimizing possible releases of radioactive substances in the event of mechanical or thermal (fire) loads. Thus the permitted activity contents of waste in bituminized form are

clearly lower than for waste encapsulated in cement/concrete because of the greater release in the event of fire. On the other hand, the different release behaviour can be offset by transport packages with sufficiently high load resistance.

The analyses of the accident risk take the following into account:

- The anticipated waste transport volume to the KONRAD waste disposal site
- The different properties of the transport packages, the form of waste product, (waste product properties), and the different activity contents
- The spectrum of possible mechanical and/or thermal accident loads
- The resultant range of accidental releases (source term)
- The spectrum of resultant potential radiation exposures taking different atmospheric dispersion conditions into account
- The frequency with which accidents and their associated radiological consequences (radiation exposure, contamination) can be anticipated

A component part of the method used is to include even very rare accident loads and to quantify the associated possible radiological consequences and frequency of occurrence of such events.

The method used is generally known as a probabilistic risk analysis and is distinguished by the fact that not only the extent of damage, for example, is stated as an assessment and evaluation criterion, but also its probability of occurrence. It is important when presenting the accident risk results that both quantities are considered simultaneously.

Modelling of complex accidental sequences requires the introduction of simplifying assumptions and categorization of accidents and incidents. The present transport risk analysis is based practically throughout on stipulations and assumptions that err on the safe side and therefore leads to a clear overestimation of the risk of possible transport accidents. This statement is backed up in the following chapters.

The principal components of the analysis of radiation exposure attributable to normal transportation and of the accident risk are represented in schematic form in Figure 2.1. The individual steps are described in greater detail below.

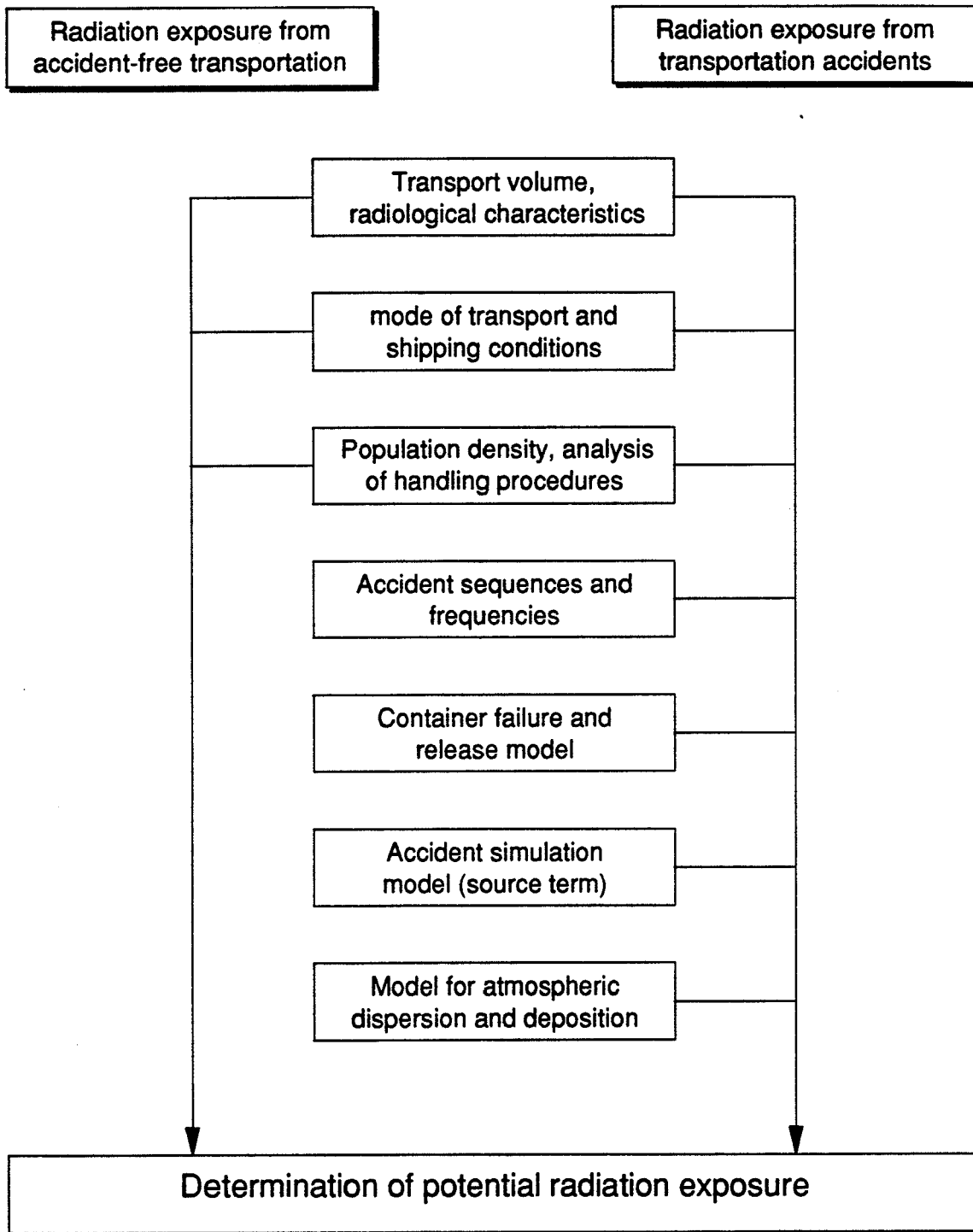


Figure 2.1: Schematic Representation of the Method for Determining the Potential Radiological Consequences from Radioactive Waste Transportation

3 Type and Quantity of Radioactive Waste Destined for Disposal

According to the current planning status, radioactive waste with negligible heat generation is destined for storage in the KONRAD waste repository in accordance with the "Provisional Waste Acceptance Requirements /BFS 90/. Waste of this kind occurs in the nuclear fuel cycle, research, medicine and technology. In its original state, the primary wastes of this type have various forms, such as:

- Liquids, concentrates, sludges
- Ion exchange resins
- Compressible and/or combustible solids
- Incompressible solids, e.g. structural material components
- Filters, filter candles
- Other types of waste

The radioactive waste is appropriately conditioned and packaged before transportation to the waste disposal site. To meet the basic requirements specified in the Waste Acceptance Requirements, primary waste must be solidified, whereby the most common solidifying agents are cement and concrete although bitumen and plastics are also used. Waste products in decomposing, fermenting or liquid form or which contain a significant fraction in such states are not accepted for disposal.

To ensure compliance with the requirements set for in the Waste Acceptance Requirements, the radioactive waste is subject to inspections as part of quality assurance procedures applied prior to being delivered to the waste disposal site.

Depending on the waste product properties, the radioactive waste is divided into six waste form groups:

- Group 01: e.g. Bitumen and plastic waste
- Group 02: e.g. Solids
- Group 03: e.g. Metal solids
- Group 04: e.g. Compacted wastes

Group 05: e.g. Cemented/concreted waste

Group 06: e.g. Concentrates in solid form

This breakdown is of particular importance in conjunction with the release behaviour in the event of incidents and accidents.

3.1 Database

The "KONRAD Provisional Waste Acceptance Requirements" contain activity limits for waste packages destined for disposal in conjunction with other requirements concerning the properties of the waste forms and waste containers. They represent the safety-related framework that must not be exceeded by the waste packages. However, they do not permit any conclusions as to the nature, quantity and properties of the radioactive waste actually occurring in the various sectors and provided for disposal. The extensive and detailed survey conducted by the Federal Office for Radiation Protection (BfS) for design and planning purposes over the recent years at potential producers and consignors of waste in the Federal Republic of Germany is of fundamental importance and has been completed in summer 1990. GRS was granted access to these data for the purpose of the present transport study. As part of waste survey waste originators had to characterize the waste packages destined for delivery to a waste disposal site, that is to say they had to indicate the waste properties with relevance for disposal and necessary for planning purposes. According to the instructions of the Federal Weights and Measures Office (PTB) and Federal Office for Radiation Protection (BfS), the data required were to represent upper bound data to allow for even unfavourable operating conditions or changes caused by the age of a nuclear facility, for instance. To enable the waste data to be summarized comprehensively a categorization model was devised on the basis of the following characteristics:

- Originator
- Container type
- Immobilization and
- Type of waste

This model was used to ensure that the waste package data were registered systematically and applied to categorize the radioactive waste occurring or anticipated to occur

in the Federal Republic of Germany in the foreseeable future, including the radioactive waste from reprocessing of spent fuel elements of German nuclear power stations that has to be accepted back from other European countries. Each waste flow is described in detail in a waste data sheet.

In detail, the spectrum of radioactive waste classified as non-heat-generating waste according to the waste survey, and suitable for disposal in the KONRAD waste repository, was subdivided into 217 reference waste types, with each reference waste type representing a certain waste form and its specific packaging. The following information is generally available for each reference waste type:

- Origin/originator
- Type of waste
- Conditioning-/immobilization type
- Type of packaging
- Radioactivity, type and quantity
- Local dose rate of the waste package
- Mean annual volume of waste

The essential characteristics of the waste data that are relevant for transportation are outlined in brief below.

3.2 Waste and Transport Container Types

A prerequisite for the handling and storage operations is the availability of a system of waste and transport containers matching to the technical safety and operating requirements of the waste repository. There are three main container designs:

- Cylindrical concrete containers
- Cylindrical cast iron containers
- Cubical containers (sheet steel, cast iron, concrete)

Without exception, these are non-recyclable waste containers with varying designs, sizes, wall thicknesses and weights. Typical examples of the different container types are illustrated in Figure 3.1 a-c.

Cylindrical concrete containers comprise a steel-reinforced concrete structure made from standard or heavy weight concrete, into which a drum filled with radioactive waste e.g. a 200 l or 400 l sheet metal drum is generally placed. The remaining annular gap and the top area of the container are sealed by concrete.

The cylindrical cast iron containers are thick-walled receptacles made of cast iron which are also used to package radioactive waste that has not been immobilized and is comparatively highly active; the wall thickness and shielding are tailored to suit the waste form concerned. These containers are sealed with a cover made from the same material, which is either screwed or welded to the body of the container.

Cubical containers are manufactured from sheet steel of at least 3 mm thickness, reinforced concrete or cast iron. They are primarily used to hold 200 l or 400 l drums or contaminated structural elements and components from nuclear installations that have been decommissioned. The largest cubical containers, such as Type V container, are designed to accommodate up to 28 x 200 l drums or 14 x 400 l drums. The cubical containers are sealed with a cover made from the same material, which is either screwed on or locked by means of tie rods. The weight of a waste container must not exceed 20 Mg (metric tons).

Table 3.1 gives an overview of the dimensions and weights of the standardized waste and transport container types. The safety requirements they must satisfy are embodied in the "Provisional Waste Acceptance Requirements" /BFS 90/.

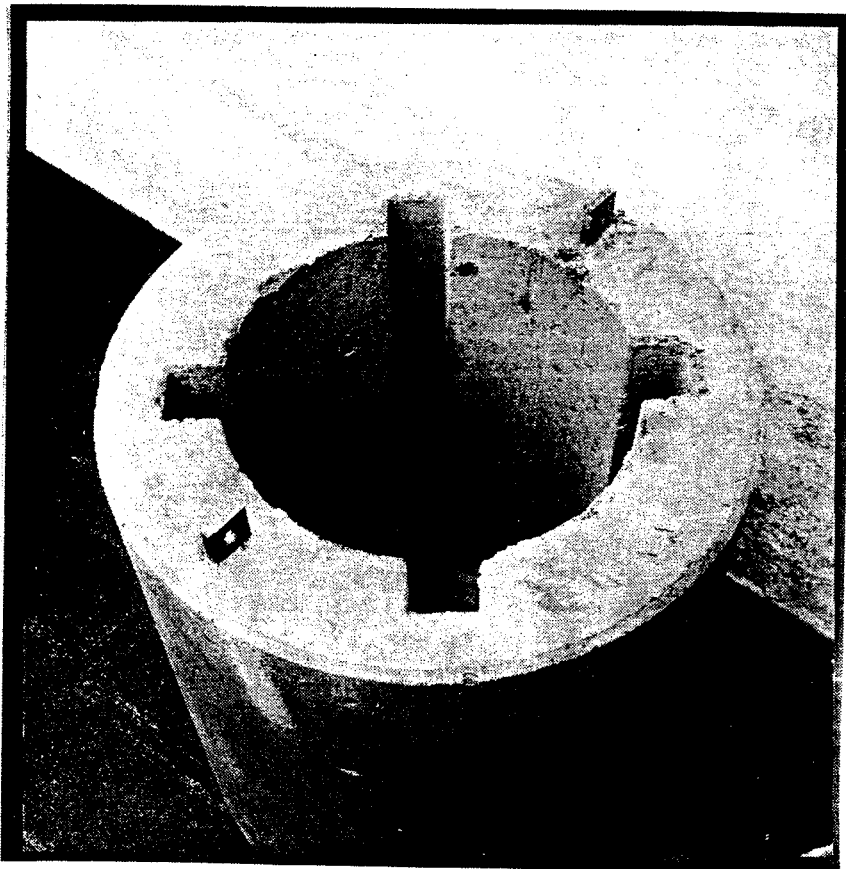


Figure 3.1a: Cylindrical Concrete Container (Type I)

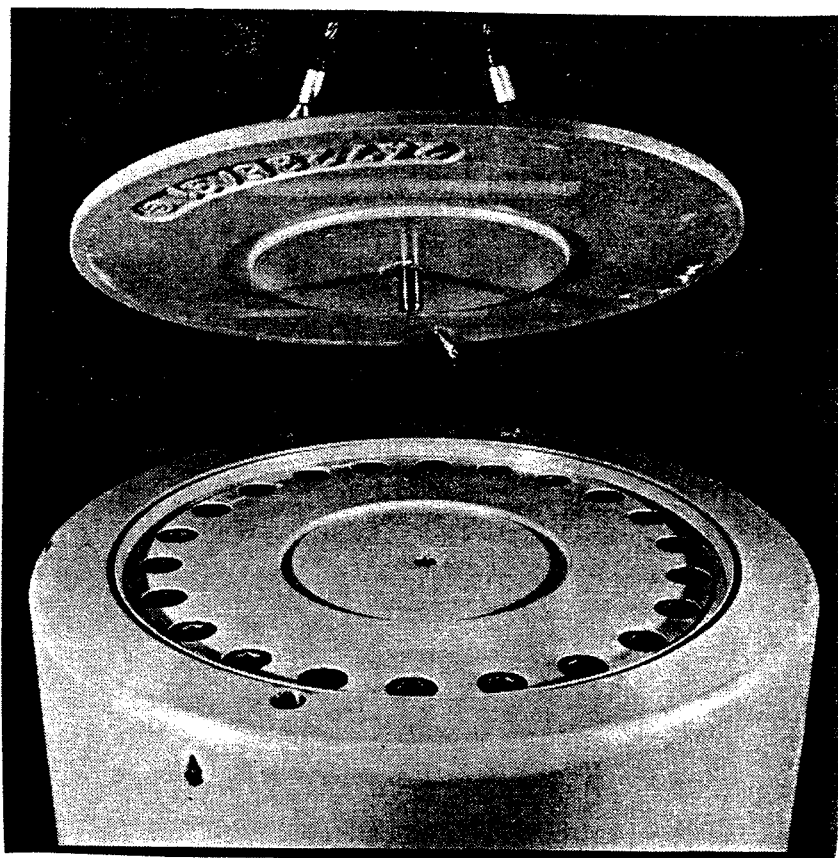


Figure 3.1b: Cylindrical Cast Iron Container (Type II)

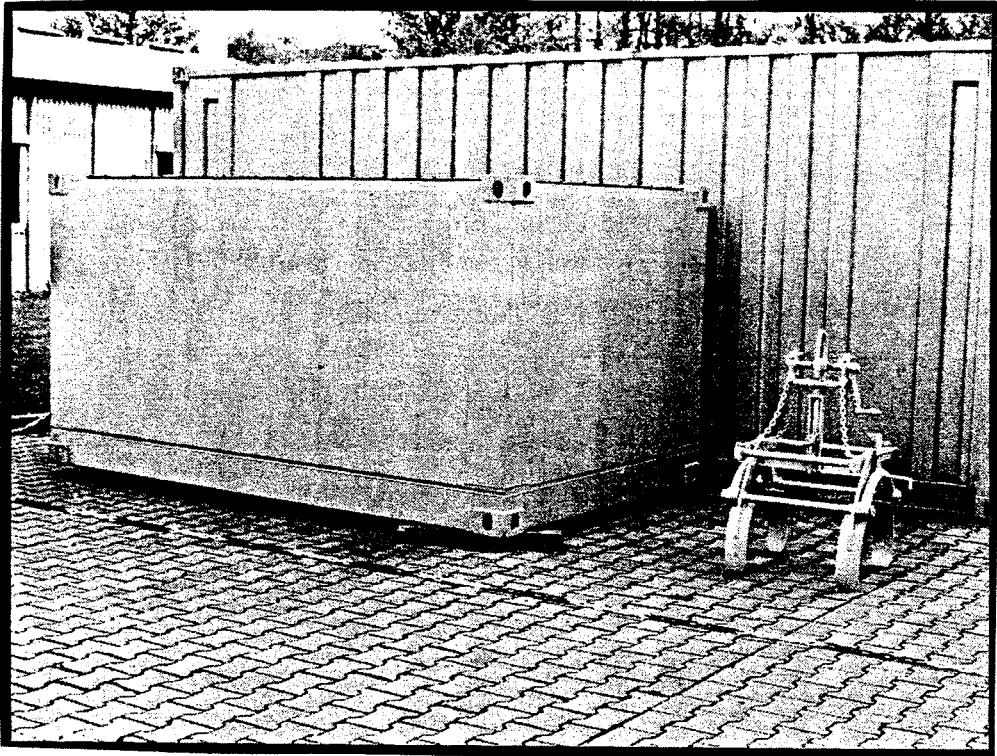


Figure 3.1c: Sheet Steel Cubical Container (Type V) and Drum Manipulator

Table 3.1: Standardized Container Types (Storage Container Classes) for Packaging Radioactive Waste with Negligible Heat Generation /BFS 90/

External dimensions						
No.	Designation	Length / Dia. (mm)	Width (mm)	Height (mm)	Gross volume (m ³)	Package weight (Mg)
01.	Concrete container Type I	ø 1060	-	1370	1.2	approx. 3...4
02.	Concrete container Type II	ø 1060	-	1510	1.3	approx. 3...4
03.	Cast iron container Type I	ø 900	-	1150	0.7	approx. 3...6
04.	Cast iron container Type II	ø 1060	-	1500	1.3	approx. 7...12
05.	Cast iron container Type III	ø 1000	-	1240	1.0	approx. 3...6
06.	Cubical container Type I	1600	1700	1450	3.9	max. 20
07.	Cubical container Type II	1600	1700	1700	4.6	max. 20
08.	Cubical container Type III	3000	1700	1700	8.7	max. 20
09.	Cubical container Type IV	3000	1700	1450	7.4	max. 20
10.	Cubical container Type V	3200	2000	1700	10.9	max. 20
11.	Cubical container Type VI	1600	2000	1700	5.4	max. 20

3.3 Waste Quantities and Transport Volumes

The operating procedures of the planned KONRAD waste repository envisage the storage of 17 shipping units in a single shift. In this context, a shipping unit is defined as either a cubical container or a pool pallet loaded with one or two cylindrical containers made of concrete or cast iron material. Per year, comprising 200 working days, 3.400 shipping units will be disposed of with single-shift operation.

On the basis of the annual waste surveys and analyses by the Federal Office for Radiation Protection, to establish the existing and newly added waste volumes single-

shift operation is regarded as being the most likely mode of operation of the KONRAD waste disposal facility and is assumed for the purposes of this study as far as the anticipated annual transport volume is concerned.

According to /BRE 90/ this supposition is backed by the substantial reductions in the annual quantities of new conditioned radioactive waste ascertained in recent years, which have led to a progressive fall in the predicted volume of waste. This development is attributed to the use of modern conditioning techniques such as high-pressure compaction, drying and packaging of waste in thick-walled cast iron containers at nuclear power stations, as well as to a reduction in the generated radioactive waste volume as a result of improved plant and process engineering at these installations. According to current forecasts, the volume of waste suitable for the KONRAD waste disposal site is expected to decrease gradually even with single-shift operation, so that this operational mode must be regarded as the most likely. This operating mode results in the annual transportation of 3,400 shipping units.

The pro rata breakdown of the transport volume (shipping units) according to the waste origin is shown in Figure 3.2 and has been derived from the waste data base already mentioned on the type and quantity of the radioactive waste occurring or anticipated in the near future in the Federal Republic of Germany (not including the new federal states). As the graph shows, a major proportion (approx. 50 %) of the transport volume is accounted for by reprocessing waste which will have to be taken back from abroad (France and Great Britain) after 1995.

The pro rata breakdown of waste container types obtained from the survey is illustrated in Figure 3.3. According to this information, cylindrical concrete or fibrous concrete containers dominate with a fraction of 50 percent. The cast iron containers account for a further 15 percent of the transport volume, with the remaining 35 percent being made up by different types of cubical container.

Categorization of Waste Volume by Origin

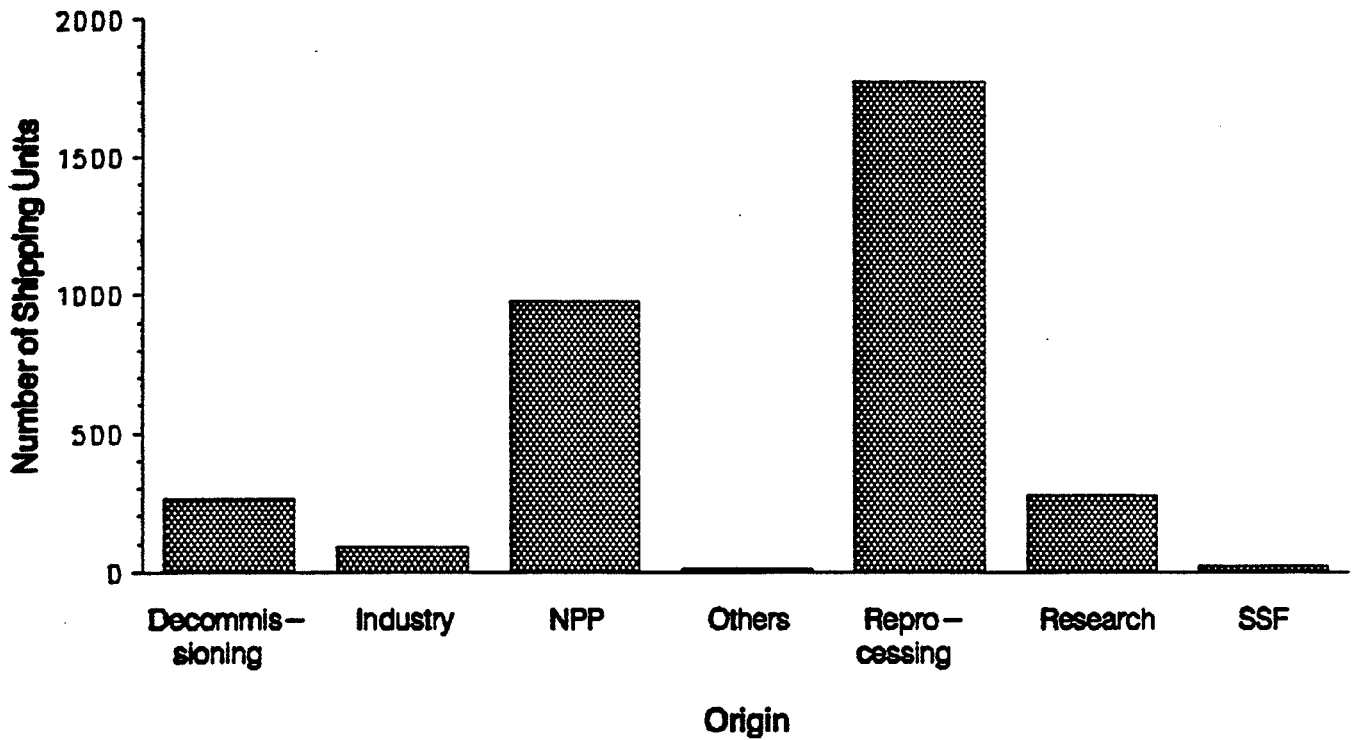


Figure 3.2

Basis: 3400 Shipping Units
SSF: State Storage Facilities

Average Annual Volume of Waste Transports (1990)

Number of Shipping Units per Package Type

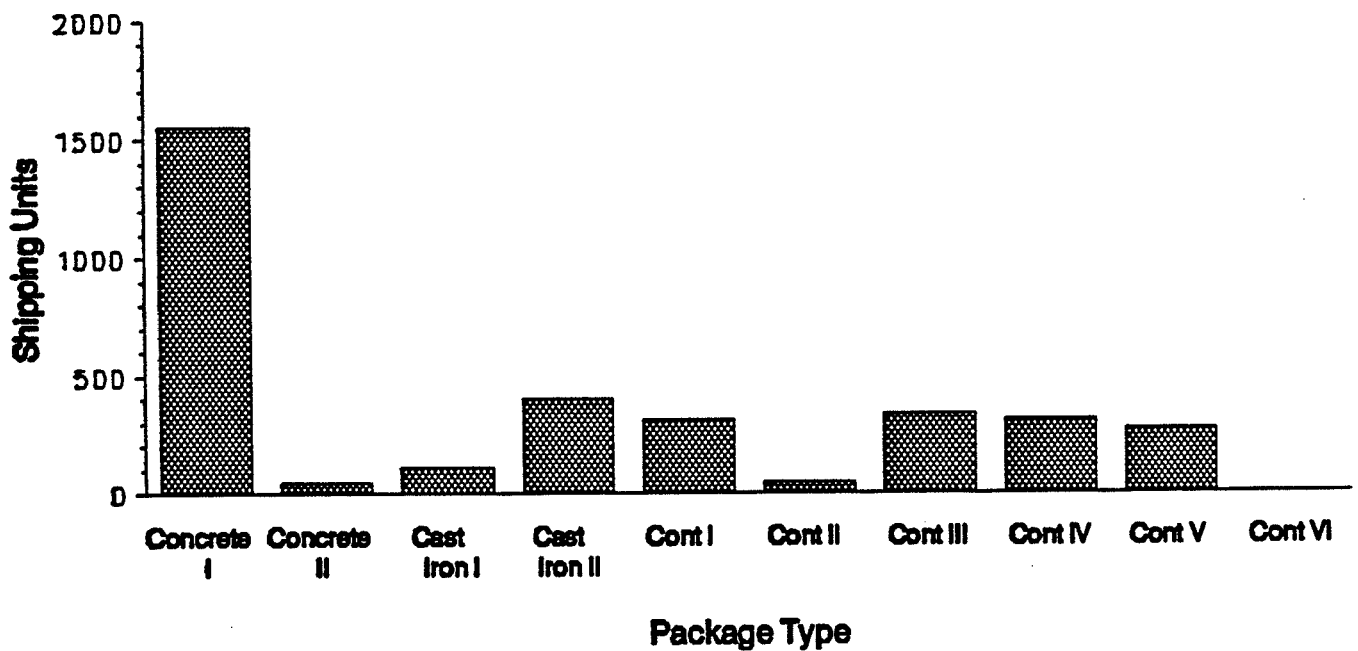


Figure 3.3

Basis: 3400 Shipping Units

4 Radiological Characterization of Waste and Transport Containers

4.1 Regulations

Depending on the consignor, the type of waste and the means of transport concerned, waste containers carried on public routes or routes to which the public has access, e.g. rail or road, are subject without exemption to the safety provisions of the relevant directives and guidelines such as the Directive on the Transportation of Dangerous Goods by Road (GGVS) and the Directive on the Transportation of Dangerous Goods by Rail (GGVE). In addition, the waste packages must satisfy the "Requirements for Radioactive Waste accepted for Disposal" according to the "Provisional Waste Acceptance Requirements" for the KONRAD repository /BFS 90/. The local dose rate of the waste package is limited by these regulations, whereby the following maximum values must not be exceeded:

	Maximum Permitted Local Dose Rate of Waste Packages at Different Distances from the Surface (mSv/h)		
	surface	1m	2m
<u>Waste Acceptance Requirements</u>			
- Cylindrical containers	2 ^{a)}	0.1	-
- Cubical containers	2 ^{a)}	-	0.1
<u>Directive on the Transportation of Dangerous Goods (GGVE/GGVS)</u>	2 ^{b)}	0.1 ^{b)}	-

a) Locally up to 10 mSv/h

b) These dose limits may be exceeded in case of exclusive use transportation, i.e. if access to the load is prevented by an enclosure and it is not loaded or unloaded between the beginning and the end of transportation. Regardless of package local dose rate, however, the maximum permitted local dose rate of the conveyance is limited to 0.1 mSv/h at a distance of 2 m (GGVS App. A, Para. 2712).

The most restrictive dose limit of the two applicable regulations shall be valid for each transport.

4.2 Local Dose Rate of Waste and Transport Containers

As a rule the gamma radiation emitted from the radioactive waste product cannot be entirely attenuated by the container, immobilization, and any shielding materials and results in a radiation field extending beyond the waste container. The size of this radiation field and the associated local dose rate depend on various factors. The dose rate is influenced by the activity content, radiation type and energy, and by the shielding efficiency of the immobilization and container materials.

Figure 4.1 shows the principal spatial distribution of the local dose rate by way of an example, in this case for Type V containers. The curve pattern corresponds to the maximum permitted local dose rate of 0.1 mSv/h at a distance of 2 m from the container surface. The curve clearly illustrates that the local dose rate declines very quickly as the distance increases and, at a distance of 15 to 25 m, falls at a levels equivalent to that caused by cosmic rays at normal aircraft cruising altitudes. At a distance of 60 to 80 m from the package, the local dose rate has tailed off so substantially and is in the range of the local dose rates encountered in our natural environment.

Extensive radiation transport and local dose rate calculations have been carried out for all waste categories in connection with the safety assessment of the designated KONRAD waste repository.

The results of these calculations are illustrated in Figure 4.2. The graph shows the distribution of the number of shipping units displaying a specified local dose rate. More than one-half (approx. 60 %) of the shipping units destined for disposal had local dose rates in the dose range of 0.01 to 0.1 mSv/h at a distance of 2 m from the container surface or shipping unit. The local dose rate of the remaining 40 percent of shipping units was below this dose range. The average local dose rate at a distance of 2 m of all the shipping units destined for disposal was around 0.03 mSv/h. Referred to the dose limit of the local dose rate of 0.1 mSv/h at a distance of 2 m from the vehicle, stipulated by the transport regulations, this figure falls below the permitted limit by at least a factor of 3. Compliance with the maximum permitted local dose rate is ensured individually by the appropriate design and configuration of suitable shielding materials.

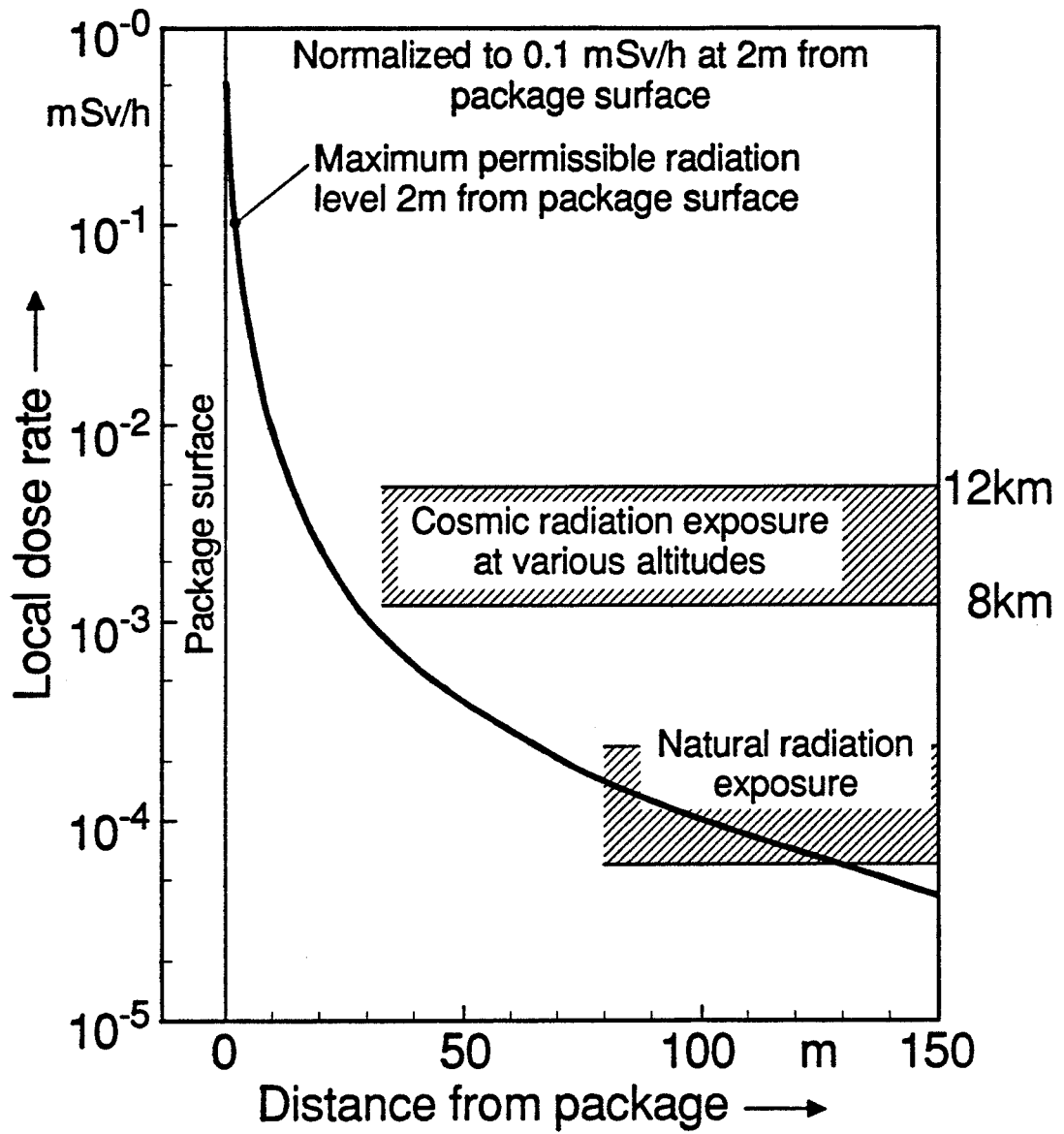
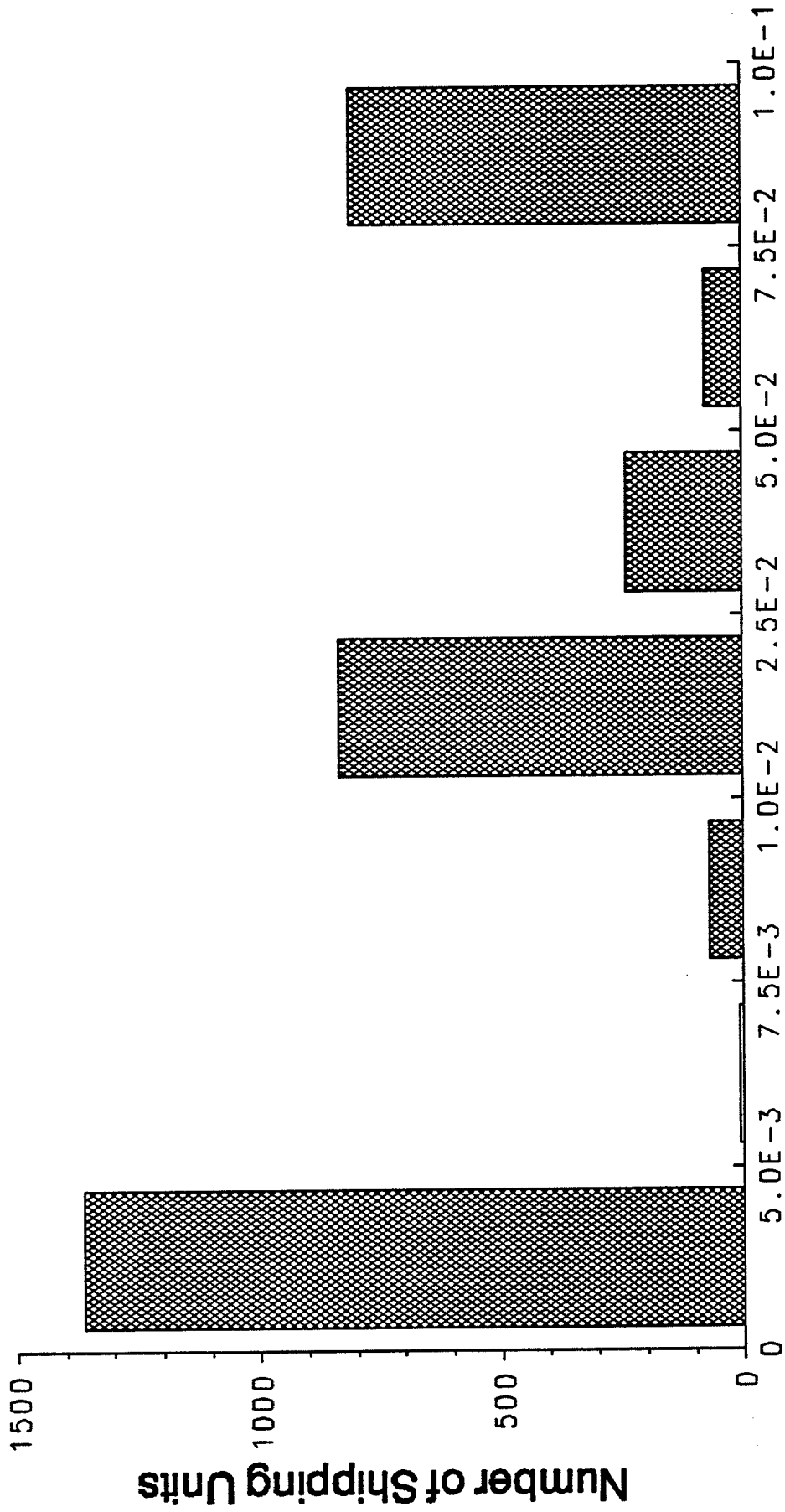


Figure 4.1: Spatial Distribution of the Local Dose Rate of a Waste Transport Container (Type V Cubical Container)

Radiation Level of the Shipping Units



Radiation Level (mSv/h) 2m from Package Surface

Basis: 3400 Shipping Units

Figure 4.2:

Figure 4.2 illustrates that the local dose rates at a distance of 2 m from the outer surface of the shipping units are distributed across a fairly large dose range for different types of waste and from various areas of origin. Even assuming that the waste producer would like to make full use of the maximum permissible dose rates, the scope for this is confined owing to the properties of the radioactive waste (e.g. limitations in volume reductions during waste processing and conditioning). In this respect, the mean dose of 0.3 mSv/h at a distance of 2 m from the shipping units, as derived from the waste data collected by the Federal Office for Radiation Protection (intended as being conservative), can be regarded as a reasonable basis for dose assessment purposes also in the longer term. The margin to the dose limit can also partially be attributed to the fact that the waste acceptance requirements are more restrictive than the transport regulations. The local dose rate limit of 0.1 mSv/h at a distance of 2 m from the vehicle embodied in the transport regulations, for example, contrasts with the local dose rate limit at a distance of 1 m from the surface of a cylindrical container according to the "Provisional Waste Acceptance Requirements", which is the more restrictive requirement.

4.3 Activity Inventory of the Waste Transport Containers

Comprehensive information on the nature and quantity of the activity contained in the waste is available from the waste data collected by the Federal Office for Radiation Protection. Figure 4.3 shows the distribution of the gross activity as a function of the number of shipping units. The figure reveals that the overall activity per shipping unit varies greatly and ranges over more than 7 decades, although the conclusiveness of this result is limited by the wide diversity in the radiological significance of different radionuclides. The majority of values occur in the range between 10^9 and 10^{13} Becquerel (Bq) per shipping unit.

Distribution of the Activity Inventory

per Shipping Unit

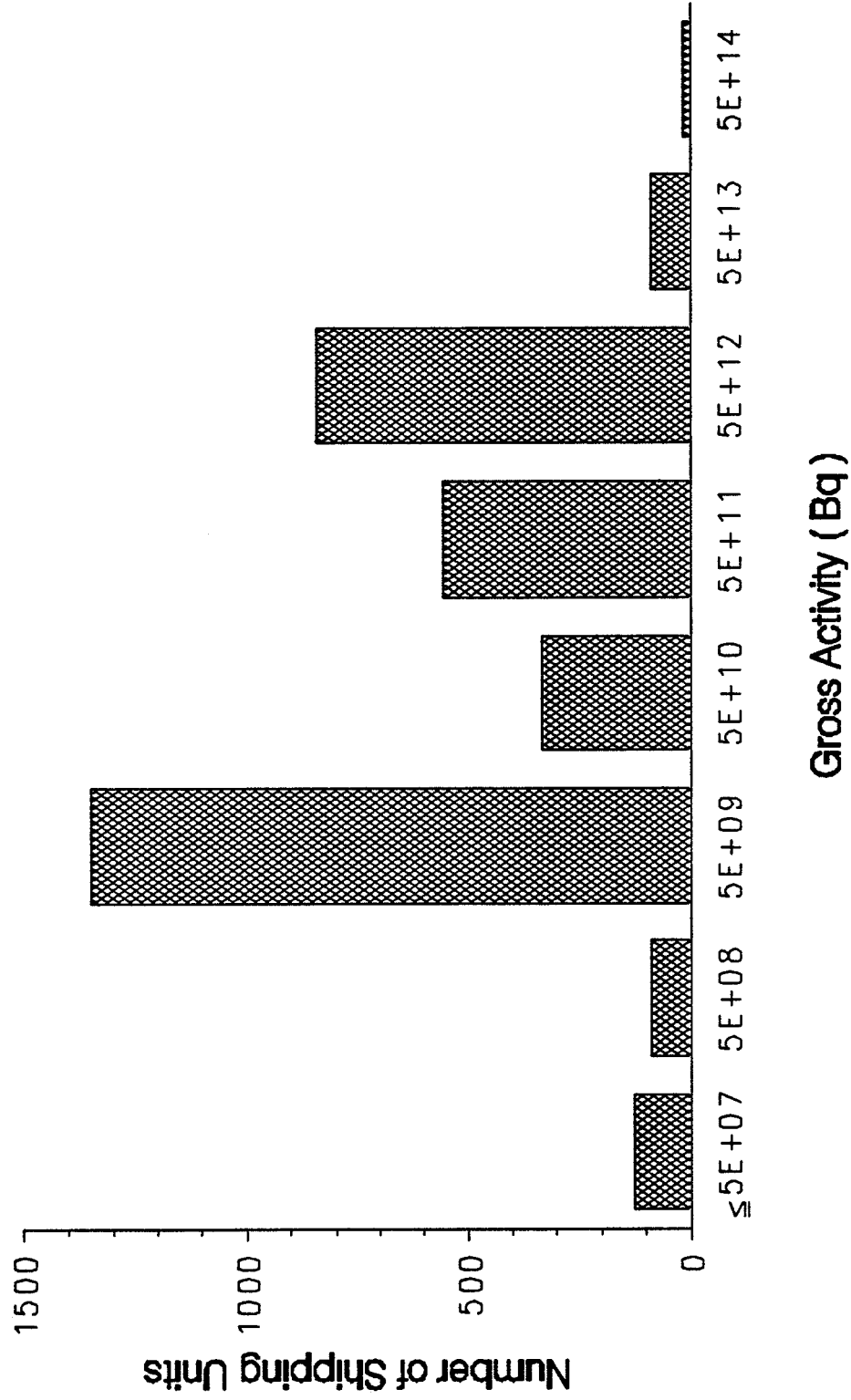


Figure 4.3:

Basis: 3400 Shipping Units

Approximately 135 radionuclides with different half-lives occur in the waste. A selection of waste nuclides relevant for the activity contained in waste or of radiological significance are listed below:

Radionuclide	Half-life	Radiation type
H3	12.3 a	β
Co 60	5.3 a	β/γ
Sr 90	28.5 a	β
Cs 137	30.1 a	β/γ
Pu 238	87.7 a	α
Pu 239	24390 a	α
Pu 241	14.9 a	β/γ
Am 241	433 a	α

5 Waste Transportation; Transport Scenarios and Arrangements

The potential radiological consequences of waste transports to the KONRAD waste disposal site depend on the nature and number of shipments and the associated waste transport routes.

5.1 Transport Scenarios

One of the objectives of the reorganisation of the German nuclear fuel cycle industry is for the German Federal Railways (DB) to be solely responsible for licenced nuclear material transports. In addition measures have been implemented to ship hazardous materials preferentially with high-safety-standard railway systems.

Consequently, the lion's share of waste bound for the KONRAD waste disposal site can be expected to be transported by rail in the future. According to forecasts made on this basis by the Federal Ministry for the Environment, Nature Conservation and Reactor Safety (BMU), a fraction of the total transport volume of approximately 80 % by rail and 20 % by road can be regarded as a reasonable transport scenario (reference case). This forecast is based on the established fact that all major consignors of radioactive waste, in terms of volume are, or will be, connected by rail to the

KONRAD waste disposal site. Insofar as this precondition is not fulfilled or transportation by rail appears impractical (e.g. for small amounts of waste or shorter travel distances, for example), consideration will be given to transportation by road. This situation is provided for in the reference scenario by the 20 % road transport fraction.

The transportation of radioactive waste by other means of transport, e.g. barge transportation in particular, is regarded as being discounted and is consequently omitted from this study.

In addition to the reference scenario, a further transport scenario envisaging transportation exclusively by rail (100 % rail) is also investigated. This approach is intended to allow for uncertainties in forecasting the exact breakdown of shipments between rail and road by means of two extreme scenarios: One (20 % road, 80 % rail), which probably overestimates the fraction of waste carried by road; and (100 % rail), which overestimates the fraction of rail transportation. This procedure also has the advantage of identifying the influence of the different shipping modes.

5.2 Transport Arrangements

In order to ensure an orderly and smooth execution of storage operations, the waste being disposed of is purposefully called for delivery concerned at the consignor's premises. The punctual delivery of the waste to the disposal site is generally the responsibility of the consignor. As a rule, only covered means of transport are used since the waste containers must be delivered in a dry condition under the "Provisional Waste Acceptance Requirements". The weight of the shipping units (loaded pool pallets and cubical containers) must not exceed 20 Mg (metric tons).

According to the information currently available, the general conditions for transportation are as follows:

- Transportation by Road

As far as the transportation of waste by road is concerned, transportation can generally be assumed to be effected directly from the consignor to the waste disposal site, primarily on main roads and motorways. The dimensions and weight of the waste pak-

kages generally necessitate the use of heavy-duty-trucks. The weight restrictions applicable in this context (maximum permissible total weight 38 Mg) suggest that the transport vehicles will essentially transport only one shipping unit.

- Transportation by Rail

Rail transportation of waste consignments to the waste disposal site will generally be performed in two stages without transfer. The first stage comprises transportation on the network of German Federal Railways (DB) as far as the interchange station in Beddingen situated a few kilometres north of the KONRAD repository. Here the Verkehrsbetriebe Peine-Salzgitter (VPS) assume responsibility for the onward movement of the waste wagons, providing a branch line service as far as the waste disposal site transfer track. The VPS network not belonging to the German Federal Railways is designed as a secure rail network with station signal control and comparable to the technical safety standards of the DB. Within the area of responsibility of the DB, a basic distinction must be made between shipments occurring as part of regular standard goods traffic and those considered to be dedicated trains.

Transportation within the framework of regular standard goods traffic is characterized by the fact that the waste consignment is transported according to a timetable on railway routes laid out as a network from junction to junction (or via several such points), and that the journey is interrupted at junction points for reformation and marshalling. This typically prolongs the transport time of a waste consignment from 1 to 3 days, whereby the wagons are generally subjected to between 3 and 5 reformations (marshalling operations). With few exceptions, waste wagons transported as part of regular standard goods traffic are generally routed through the Hanover/Seelze and Braunschweig marshalling yards.

Waste wagons transported as dedicated train, are not subject to marshalling operation and long interruptions - apart from stops necessitated by operating requirements - but travel direct from the consignor to the waste disposal site or Beddingen interchange station. The marshalling yard in Braunschweig is generally bypassed. However, the operating conditions at the waste disposal site make the transportation of waste by dedicated trains conditional on the consignor concerned being able to have sufficient

quantities of waste packages on a call-up basis available. For the purposes of the present study it is assumed that these conditions are fulfilled, in particular as regards the waste volume from German light-water reactors following spent fuel element reprocessing abroad. In the case of other consignors, however, transportation as part of regular standard goods traffic is assumed for the purpose of this study.

Once the waste wagons have been delivered to Beddingen interchange station, current plans envisage their onward movement as quickly as possible by VPS with the aim of reducing standing times to a minimum. If the waste wagons are delivered in a mixed-cargo train, i.e. with wagons with different destinations, onward transportation from Beddingen will be preceded by reformation or marshalling activities.

Current planning envisages the use for transportation of slightly modified Shimms 708 and Sahimms 900 wagons which have a load capacity of at least 2 shipping units per wagon, depending on the type of package. These are 4 or 6-axle flat bogie vehicles designed specifically for shipping moisture-sensitive goods of high weight. Figure 5.1 shows a schematic representation of the dimensions of a Sahimms Type 900 wagon.

The travel and handling times of the waste consignments and personnel required for railway transportation were established in cooperation with the DB (Mainz, Hannover, Braunschweig), the Verkehrsbetriebe Peine-Salzgitter GmbH (VPS) and time-and-motion studies conducted at the Braunschweig marshalling yard and Beddingen interchange station. In this respect, the following dose calculations take the circumstances at these transfer stations into account.

The maximum permitted travel speed for regular goods train are laid down in the train operation regulations and are as follows for goods wagons that are not intended for high-speed transports:

- Normal transport 80 - 100 km/h
- Marshalling operations 25 km/h

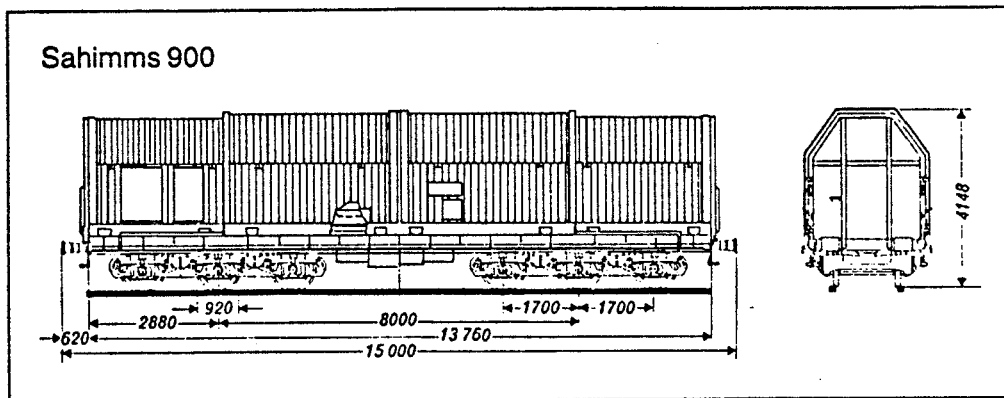


Figure 5.1: Schematic Representation of the Sahimms 900 Goods Wagon

5.3 Traffic Volume

The estimation of the road and rail traffic volume associated with waste transportation is based on the information regarding the quantity of waste provided by the individual waste consignors. In addition, the disposal capacity of 17 shipping units (SU) per day or 3,400 shipping units per year, with single-shift operation, and the above ground buffer storage capacity of the waste disposal facilities must also be taken into account. The size of the individual waste shipments delivered from the consignor, which can consist of several wagons in the case of transportation by rail, has been assumed as follows:

Mode of transportation	SU per shipment
Truck	1
Regular goods train	2 - 17
Dedicated train	40

The number of waste shipments per year determined on this basis is stated in Table 5.1 for both transport scenarios considered in this study. The values given are approximate values.

Table 5.1: Estimated Number of Waste Shipments to the KONRAD Waste Repository Site Assuming Single-shift Disposal Operation (3,400 Shipping units per year)

Mode of Transportation	Mean Number of Shipments per Year	
	80% rail/ 20% road	100% rail
Rail		
- regular goods train	approx. 200	approx. 345
- dedicated train	approx. 45	approx. 45
Road (Heavy trucks)	approx. 680	

According to Table 5.1 and assuming a breakdown of 80 % rail to 20 % road, the waste-related traffic volume for the most probable transport scenario is approximately 200 regular goods train shipments, approximately 45 dedicated-trains and approximately 680 truck shipments per year. The 45 dedicated train loads correspond to a waste volume of approx. 1,785 SU, arising from the reprocessing of spent fuel elements from German reactors which will have to be taken back from other countries from the mid-1990s onwards. The 200 or so shipments belonging to standard goods traffic comprise the waste generated by different consignors in the Federal Republic of Germany, totalling some 935 SU. Waste consignments carried as part of regular goods traffic thus comprises 5 shipping units on average or, assuming a loading capacity of 2 SU per wagon, two to three wagon per shipment.

In the event of exclusive waste transportation by rail (100 % rail scenario), the number of shipments carried by regular goods traffic increases from around 200 to approximately 345. This increase corresponds to the equivalent of the annual waste volume of 680 SU which would have to be transferred from road to rail.

As far as the waste-related traffic volume in the region of the waste disposal site is concerned, the numerical values stated above represent upper limit values since some waste consignments from different originators may be carried in the same train following marshalling. This situation is also taken into account accordingly when investigating the accident risk.

The numerical values in Table 5.1 characterizing the traffic volume attributable to waste transport must be seen against the "background" of the total volume of goods traffic in the region of the waste disposal site. As far as the repository region (see Figure 5.2a) is concerned, the following data provided by the German Federal Railways Directorate in Hannover are available as regards the daily goods train traffic in 1989 (Table 5.2).

Table 5.2: Daily Number of Goods Trains in the Region of the Waste Disposal Site

Route	Goods train per Day
Lehrte - Groß Gleidingen	108
Hildesheim - Groß Gleidingen	18
Groß Gleidingen - Braunschweig marshalling yard	82
Groß Gleidingen - Beddingen	61

As far as the volume of road traffic in the region is concerned, the "average traffic volume per working day (DTV-W)" according to the 1985 traffic census, as shown in Table 5.3, serves as an approximate aid to orientation /BAS 86/. Insofar as the numerical values refer to the Hannover-Berlin motorway (A 2), considerable changes have taken place in the time since the survey was conducted.

Table 5.3: Traffic Volume in the Repository Region According to the 1985 Road Traffic Census

Route	Goods Traffic	Passenger Traffic
	(Vehicles per day)	
Secondary Roads	183	2 103
Main Roads	547	5 058
A 39 / A 391 Motorway (Salzgitter - Braunschweig)	2 122	16 140
A 2 Motorway (Hannover - Berlin)	4 423	15 194
A 7 Motorway (Kassel - Hannover)	6 401	26 238

The figures indicate that the road and rail traffic volume associated with the transportation of waste does not cause any noticeable change in the traffic situation and vehicle density.

5.4 Routing

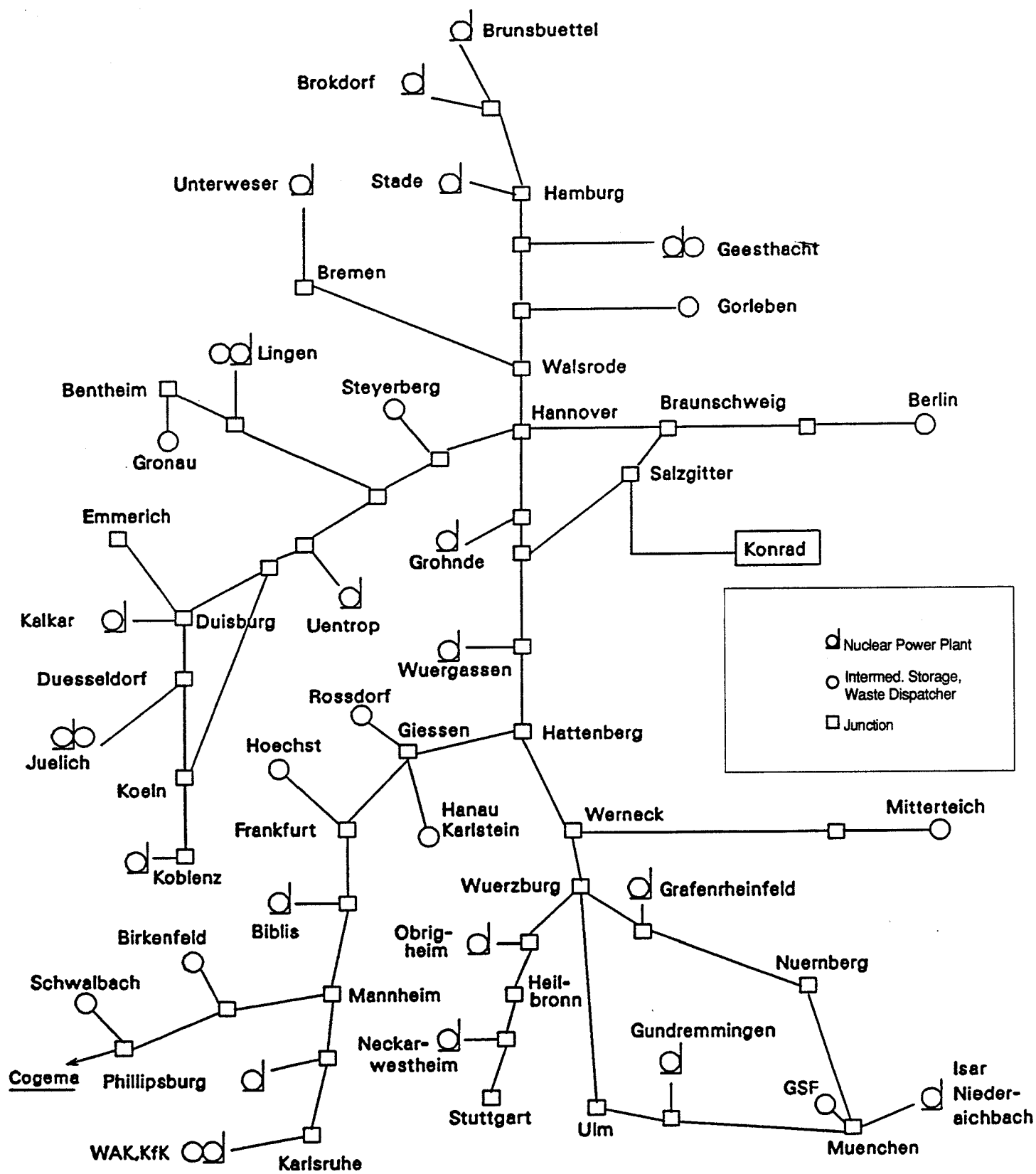
The routing or itinerary of the waste transports is largely determined by the geographic location of the various dispatch locations and the waste disposal site (Figure 5.2a).

The itineraries identified in the road route map (Figure 5.2b) correspond to the most favourable routes and largely coincide with the motorway and main road networks.

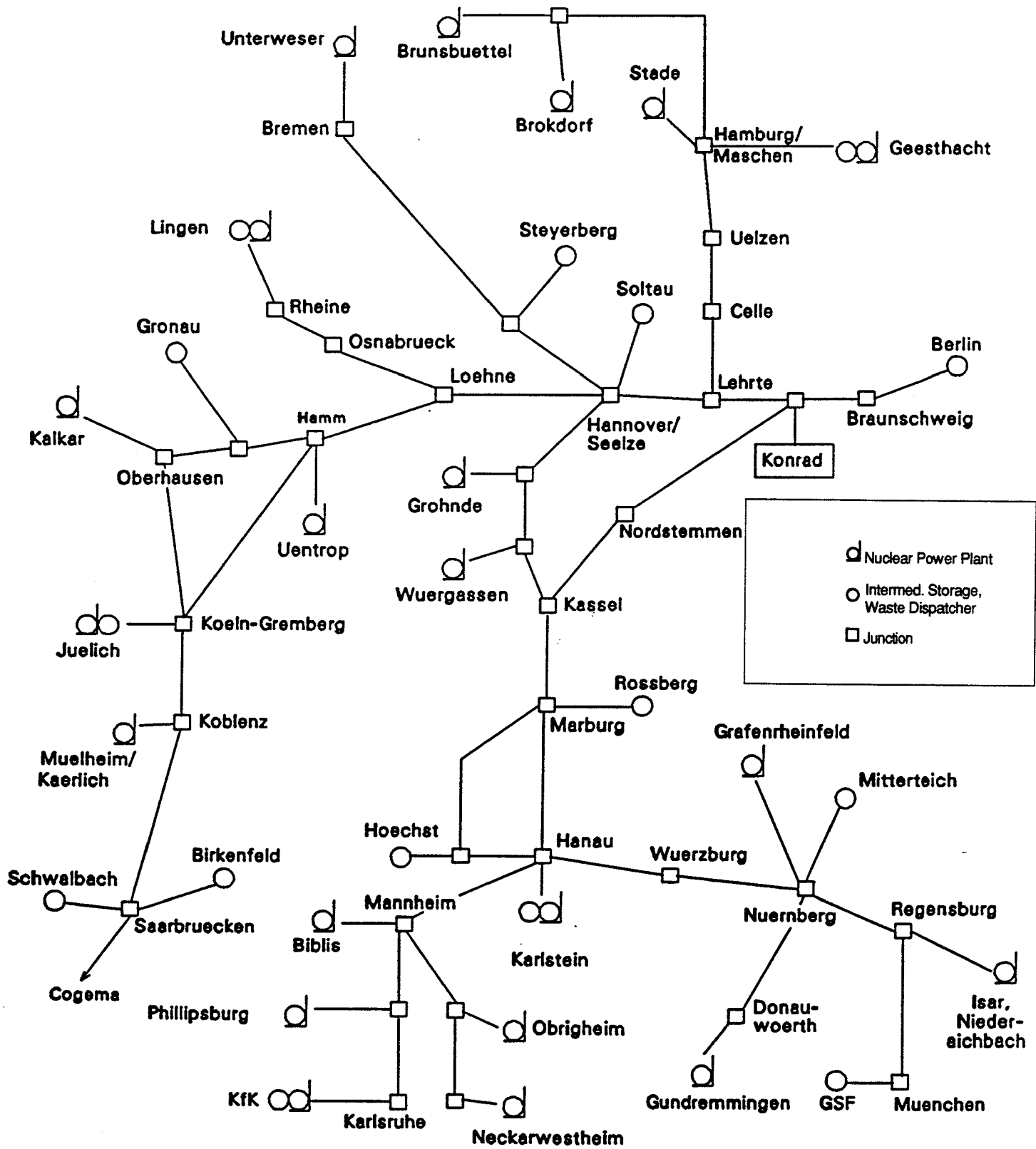
The rail route map (Figure 5.2c), by contrast, is based on information from the German Federal Railways which provided route plans for each individual consignor for the purpose of this study. We note, however, that the information provided is generic and does not rule out alternative routes.



Figures 5.2a: Region of the Planned KONRAD Waste Disposal Site /May 90/



Figures 5.2b: Waste Transportation by Road; Routing



Figures 5.2c: Waste Transportation by Rail; Routing

6 Radiation Protection Regulations

The basis for the radiation protection that apply to the transportation of radioactive materials are the Atomic Energy Act related provisions in the Radiation Protection Ordinance (StrlSchV) and the provisions of the Directives on the Transportation of Hazardous Goods. The applicability of the Radiation Protection Ordinance is, however, limited as the provisions of §§ 29 to 80 do not apply to the transportation of radioactive materials according to current legislation, with the exception of the principles of radiation protection contained in § 28 (e.g. minimization principle).

The relevant radiation protection regulations are therefore based on the specific Directives on the Transportation of Dangerous Goods by Road (GGVS) and by Rail (GGVE). This national traffic regulations on the transportation of radioactive materials are based on the International Atomic Energy Agency (IAEA) "Regulations for the Safe Transport of Radioactive Materials (Safety Series No. 6)", the last revised edition of which was published in 1985 /IAE 85/.

Under these regulations, the radiation exposure is controlled by a system of dose and dose rate limitations. The radiation exposure of the transport personnel is generally limited to 5 mSv/a. This value may be exceeded - up to a maximum dose of 50 mSv/a - only if the individuals are classified as being occupationally exposed to radiation and are subject to individual radiation exposure monitoring and regular special health supervision.

Internal measures within the area of responsibility of the DB have been in place for years to ensure that the aforementioned dose limit of 5 mSv/a is not exceeded.

A maximum permitted dose of 1 mSv/a is stated in the IAEO regulations for the general population with the provision that this value be used as a limit for the critical group of people. If compliance with this dose limit can be proven for the critical group, then the radiation exposure of the general population is generally well below this dose limit.

In addition to the local dose rate limit for the waste containers (cf. Chapter 4), further local dose rate limits are stipulated in the traffic regulations for the means of transport. Thus, in particular, the local dose rate outside the vehicle must not exceed the following values irrespective of the nature and quantity of the radioactive load:

Max. permitted local dose rate

- External surface of vehicle: 2.0 mSv/h
- At a distance of 2 m from the vehicle: 0.1 mSv/h

The maximum exposure levels apply equally to road and rail transport. In conjunction with road vehicles, also note that the local dose rate at the driver's and co-driver's seats must not exceed 0.02 mSv/h unless the personnel is regularly subject to special health supervision.

Table 6.1 provides an overview of the maximum permissible body doses and local dose rates.

Table 6.1: Permissible Exposure Levels for the Transportation of Radioactive Waste

Regulations		Maximum Permissible Doses or Local Dose Rates	
GGVS/GGVE	Vehicle	external surface	2.0 mSv/h
		2m from external surface	0.1 mSv/h
		drivers cab ^{a)}	0.02 mSv/h
IAEA	Transport Personnel	5 mSv/a	

a) Specified only for transportation by road (GGVS)

7 Radiological Consequences from Normal (Accident-Free) Waste Transportation

On the basis of the waste transport volume, the radiological characteristics of the waste and transport containers, and the transport arrangements dose estimates were carried out for various groups of people for the two transport scenarios considered in this study (80 % rail/20 % road and 100 % rail). In order to assess the radiation exposure with accident-free transportation, the collective and individual doses are considered on the basis of the effective dose concept.

In this context, the collective dose can be seen as a quantity which provides particular information about the extent to which the transport personnel and the population as a

whole, that is to say collectively, are exposed to radiation as a result of waste transportation. This radiological quantity can be compared with the exposure of the population by natural sources and the application of ionizing radiation and radioactive materials in other areas of human activities, for instance.

The individual dose or effective dose can also be used as a comparative quantity, for instance, in conjunction with natural radiation exposure and its range of variation. In addition, it is useful in showing compliance with relevant radiation protection regulations.

The collective dose anticipated as a result of waste transportation was determined using the INTERTRAN computer program /IAE 83/ provided by the International Atomic Energy Agency (IAEA), Vienna. This program system can be used to establish the collective dose for different population groups, taking the relevant traffic, routing and radiological basic data into account. Three different groups of people were considered in the study:

- Transport personnel, e.g. vehicle driver, assistant
- Dispatch and marshalling personnel
- General population

The category of the general population includes all residents or passers-by living within a corridor 800 m deep on either side of the transport route, the people in vehicles meeting or overtaking the vehicle carrying the waste, as well as any people exposed at stopping places for road transporters (e.g. service stations). The shielding effect of buildings was considered only for the group of people comprising residents in areas with urban housing structure.

The individual dose estimates are based on an analysis of the exposure conditions to which individuals or groups of people might be exposed on the transport route of the radioactive waste. The dose is then derived from the distance-dependent local dose rate, the typical traffic volume for that locality, as well as the place and duration of exposure of the people concerned.

7.1 Collective Doses

With single-shift operation of the waste repository and an annual disposal capacity of 3,400 shipping units, the transportation of radioactive waste leads to collective doses stated in Table 7.1 for the two transport scenarios considered in this study.

Table 7.1: Annual Collective Doses for Different Population Groups

Population group	Annual Collective Dose (man - Sv/a)	
	80% rail / 20% road	100% rail
Transport personnel	approx. 0.1	approx. 0.03
Marshalling and dispatch personnel	approx. 0.1	approx. 0.14
General population	<u>approx. 0.1</u>	<u>approx. 0.03</u>
Total ^{a)}	approx. 0.3	approx. 0.2

a) The fraction of the collective dose attributable to the area around the site (25 km radius) is approximately 30% of the total

The estimates of the collective dose refer to the entire territory of the Federal Republic of Germany (excluding the states of the former GDR) and are derived from the waste transportation arising and being carried out throughout the country. Depending on the transport scenario, the portion of the collective dose accounted for by people directly involved in transport activities, namely transport, marshalling and dispatch personnel, is on the order of 0.17 to 0.2 man-Sv per year, accounting for more than two-thirds of the total collective dose anticipated as a result of waste transportation. With 15 to 30 percent of the total collective dose, the portion of the collective dose affecting the population is relatively small despite the fact that this group far exceeds the people exposed for professional reasons by number. This can be attributed primarily to the fact that residents living along the transport route are generally exposed to the field of radiation emanating from the waste containers only for a very short time.

The collective dose values also reveal that waste transportation by rail results in slightly lower collective doses than the transport scenario with a 20 percent road transport.

A comparison with the collective dose resulting from the natural radiation to which the group of residents/passers-by is subjected permits the evaluation and overall classification of the collective dose anticipated as a result from waste transportation. On its own, the terrestrial component of natural radiation (that is to say excluding cosmic and internal components) caused by radionuclides present in soils and building materials amounts to approximately 0.5 mSv/a for the Federal Republic of Germany, whereby regional deviations reveal values up to two or three times this figure /BON 90/. The resultant collective dose of people living in property on or adjacent to the assumed transport routes amounts to an estimated 800 man-Sv/a, assuming a mean population density of 250 people/square kilometre, a route network length of around 4,000 km and a corridor depth on both sides of the transport route (in line with the INTERTRAN program) of 800 m.

If this numerical value is compared with the collective dose anticipated as a result of waste transportation (Table 7.1), the collective dose from waste transportation is found to account for only fractions of the natural exposure. Given the small absolute amount of the collective dose caused by waste transportation on the one hand and the only slight differences between the transport scenarios on the other, no clear preferences can be deduced from the collective dose investigations as regards a specific mode of transport.

7.2 Individual Doses

The individual dose estimates made by the present study were determined for locations and professional functions distinguished by a high transport volume, the transport arrangements etc., and the associated potential radiation exposure. In this context, the individuals or groups of people considered were generally those likely to be exposed most extensively to the radiation emanating from the waste containers as a result of their living habits or profession. These individuals or groups of people are usually described as the "critical group". They include residents living along the envisaged transport routes all the year round or railway personnel directly involved with waste transportation, such as dispatch and marshalling staff at the relevant transfer stations. The radiation exposure of any other people falls short, and in most cases far shorter than the dose values calculated for the critical group.

In estimating the radiation exposure of the residents along the route or passers-by, the following exposure components were taken into account:

- First, the exposure component from all waste consignments transported via the route concerned during the passage of the transport vehicle at a distance of 5 m (road) or 10 m (rail).
- Second, an additional exposure component caused by every 20th waste consignment (or 5 percent of the route-specific transport volume) during randomly distributed traffic-related stopping times (duration 2 to 5 minutes) of the transport vehicle en route, e.g. at traffic lights or railway signals.

Doses at specific transfer stations, such as Braunschweig marshalling yard, Beddingen interchange station, or the transfer track at the KONRAD repository installation, were calculated in compliance with the current local circumstances and work practices, e.g. shift operation. Due attention was paid here to the spatial distances between the waste wagon and the place where exposed persons are located, and the duration of exposure. In this context, the operating methods at the Braunschweig and Beddingen marshalling yards were analyzed in greater detail. It was further assumed that the individuals or groups of people being considered were assigned exclusively to a particular professional function, such as the reception sidings or, at Braunschweig marshalling yard, to the Beddingen marshalling track, for example, and that they worked there.

Shielding by building structures (mean attenuation factor DRF = 10) was taken into account on a time basis (75 % spent indoors, 25 % outdoors) only with the group of people residing next to the marshalling yard.

The doses for the critical groups of people derived on this basis are upper estimates. Under normal transport conditions and consideration of the general peripheral conditions (e.g. single-shift storage operation), these values will practically not be exceeded, even in the region with the highest local waste transport volume, that is the region of the waste disposal site. Outside the repository region, the values generally fall far short of the stated doses in line with the reduced route-specific transport volume.

The calculated individual doses are summarized in the Tables 7.2 to 7.4. Table 7.2 shows the individual dose for residents and passers-by along the (road) transport

route according to the transport scenario assuming 20 % of shipments by road. The radiation exposure of the population and the transport/dispatch personnel in case of exclusive waste transportation by rail (100 % rail) is presented for selected locations and transfer stations in Tables 7.3 and 7.4. The dose values therefore conservatively bound the 80 % rail/20 % road transport scenario.

The results (Tables 7.2 and 7.3) indicate that the predicted potential radiation exposure of the population (critical group of people) as a result of waste transportation by rail generally lies in the dose range from 0.02 to 0.1 mSv/a. Higher doses although still representing only fractions of natural radiation exposure, are found for residents of buildings immediately adjacent to the marshalling yard in the area of Alte Salzdahlumer Road (minimum distance to track 20 to 30 m), whose potential radiation exposure - according to the relevant assumptions (100 % rail transport and continuous presence all year round) - could reach maximum values up to 0.2 mSv/a.

However, bearing in mind the current planning stage, which assumes that part of the waste (up to 20 percent) will be conveyed by road, the predicted radiation exposure for the critical group of people will be approximately 0.1 mSv/a in the area of Alte Salzdahlumer Road as well. This reduction in the potential radiation exposure (from 0.2 to 0.1) corresponds to the reduced volume of waste being transported via the Braunschweig marshalling yard: the total of approximately 345 consignments a year with exclusive rail transportation is reduced to only around 200 consignments when up to 20 percent of the waste volume (= 680 shipping units) is transferred to road transportation (cf. Table 5.1).

Note in particular that the described exposure situation in the vicinity of the marshalling yard is restricted entirely to the residents of the buildings directly adjacent to the railway embankment in the Alte Salzdahlumer Road. By no account does it apply to other locations in the vicinity of the marshalling yard. This phenomenon is associated with the fact that the residents of these buildings are more exposed to the radiation field emanating from the waste containers than any other population group within the marshalling yard area owing to the marshalling operations and the associated wagon standing times. The transport volume travelling by dedicated trains on the other hand, has no effect at all on the radiation to which people living by the marshalling yard are exposed since the dedicated train loads are directed straight to Beddingen interchange station and made ready for dispatch there.

In the hypothetical case of waste transportation exclusively by means of regular goods trains (no dedicated trains), and assuming that all movements (over 3,400 shipping units) pass through Braunschweig marshalling yard, the radiation exposure of the residents living at the marshalling yard (critical group of people) could potentially increase to 0.4 mSv/a.

The use and share of dedicated trains for shipping radioactive waste therefore have a significant influence on the potential radiation exposure of the immediate residents and transport personnel of the Braunschweig marshalling yard. In the context of the present study, this mode of transport was assumed only for the waste contingent derived from reprocessing abroad owing to the large volume concerned. The use of dedicated trains to transport the waste from consignors in the FRG who also have a sufficiently high waste volume to dispose of could lead to a further reduction in the radiation exposure.

With regard to people professionally concerned with waste transportation, the critical group of people primarily comprises the dispatch and shunting personnel of German Federal Railways and the Verkehrsbetriebe Peine Salzgitter at the Braunschweig marshalling yard and Beddingen interchange station with function in marshalling/dispatching the waste wagons. Depending on the job concerned, maximum dose values of around 0.3 to 0.7 mSv/a have been determined for this relatively small group of people; the values for the other marshalling personnel are clearly lower.

The radiation exposure of the marshalling and dispatch personnel thus lies in a dose range that was also observed in other railway areas with a high volume of radioactive consignments /BZA 90/. In any case, compliance with the relevant dose limit of 5 mSv/a, as applicable to this group of people, is ensured.

The current information level does not permit accurate dose estimates to be made for people professionally exposed to radiation as a result of waste transportation by road. Such consideration require the availability of sufficiently detailed information as regards the transport sequence, vehicle type, and personnel management. Unlike rail transports, established data are currently not available in this connection permitting the individual doses to which the transport personnel are subjected as a result of waste transportation by road to be estimated. In general, however, it must be noted that the radiation protection principles and the regulations governing dose and dose rate li-

mitation according to Chapter 6 retain their full validity for transportation by road. If necessary, the road transport personnel must be classified as being occupationally exposed to radiation and therefore subject to regular radiation protection procedures.

Table 7.2: Estimates of the Annual Radiation Exposure of the Public (Critical Group) as a Result of Waste Transportation by Road

Transport Scenario: 20% Road / 80% Rail		
Route	Population Group ^{a)}	Effective Dose (mSv/a)
Motorway A 39	Residents in adjacent property / passers-by	< 0.02
Northern Industrial Route (Salzgitter)	Residents in adjacent property / passers-by	< 0.02
Access road to KONRAD Shaft Installation	Employees of the slag reprocessing plant	< 0.03 ^{b)}
Natural Radiation Exposure		ca. 2.0

a) Time spent exclusively outdoors

b) Vehicle waiting time at the entrance checkpoint ≤ 20 min.

Table 7.3: Estimates of the Annual Radiation Exposure of the Public (Critical Group) as a Result of Waste Transportation by Rail

Transport Scenario: 100% Rail Transport with Regular Goods Trains and Dedicated Trains		
Route	Population Group	Effective Dose (mSv/a)
Hannover/ Braunschweig/ KONRAD Repository	Residents in adjacent property ^{a)}	< 0.04
Hildesheim/Groß-Gleidingen	Residents in adjacent property ^{a)}	. ^{b)}
Braunschweig Marshalling Yard	Residents of the buildings closest to the track, Alte Salzdahlumer Road	0.1 - 0.2 ^{c)}
	Residents of the area to the north-east of the marshalling yard	< 0.05
Beddingen Interchange Station	Residents in adjacent property	< 0.05
Transfer Track Shaft Installation	Employees of the slag reprocessing plant	< 0.1
Natural Radiation Exposure		2.0

a) Time spent exclusively outdoors

b) Transport volume small by comparison with other routes according to current information

c) Value range for the critical group of people for

- Transport scenario 80% rail / 20% road (lower value)

- Transport scenario 100% rail (upper value)

Table 7.4: Estimates of the Annual Radiation Exposure of the Transport Personnel as a Result of Waste Transportation by Rail

Transport Scenario: 100% Rail Transport with Regular Goods Trains and Dedicated Trains		
Route / Functional Area	Functions	Effective Dose (mSv/a)
Braunschweig Marshalling Yard		
Approach Line	Reception inspectors	< 0.7
Sorting Sidings	Marshalling personnel ^{a)}	< 0.6
Exit Sidings	Marshalling personnel ^{a)}	< 0.4
Beddingen Interchange Station		
Approach Line	Reception inspectors	< 0.7
Sorting Sidings	Marshalling personnel	< 0.7
Exit Sidings	Transfer traffic	< 0.2
Natural Radiation Exposure		2.0

a) Fulltime job at Beddingen marshalling track

8 Transport Accident Risk

8.1 General Procedure

On their way to the waste disposal site, waste transports can become involved in accidents. In certain circumstances the waste containers may not be able to withstand the accidental forces, thus causing radioactive substances to be released into the environment. Depending on the radioactive materials held in the waste containers concerned and the amount released into the environment, the radiological consequences - such as radiation exposure of men and contamination of the biosphere - vary over a wide range. The frequency with which specific consequences can be anticipated for the waste transport volume being considered depends on several variables, including the following:

- The frequency with which varying accidental forces affect waste containers
- Properties of the waste containers and the waste product they contain, which determine the release behaviour
- The radioactive content (activity inventory)
- The frequency with which different atmospheric dispersion conditions are present: these can influence the airborne and precipitated contaminant concentrations and the subsequent potential radiological consequences.

To determine the risk resulting from transport accidents as regards the transport volume to the KONRAD waste disposal site, the spectrum of possible radiation exposure is determined and, at the same time, the probability of occurrence of such radiological consequences is quantified.

The waste containers are primarily delivered by rail, but a small proportion, currently estimated at a maximum of 20 % of the shipping units delivered, arrives by road. The investigations of the risk associated with transport accidents refers to the close-in region of the planned waste repository. The region is defined as being within a radius of 25 km of the installation, thus covering the area in which all waste transports to the waste disposal site are concentrating. In this context, two basic transport scenarios are used:

- 100 % rail transport
- 80 % rail / 20 % road transport

The size of the region around the site for which the accident risk arising from waste transports is determined was selected because it encompasses all the waste transports converging in the waste disposal site region and the rail and road routes representative for the area. It includes Braunschweig marshalling yard, through which a large proportion of the waste transports are expected to be directed.

The determination of accident frequencies is based on accident statistics for railway goods traffic and heavy goods traffic on federal motorways and similar main roads throughout the entire territory of the Federal Republic of Germany (before the accession of the GDR). This comprehensive statistics can be applied to the area around the waste disposal site since it has no less favourable traffic conditions than the larger area to which the accident statistics refer. This statement does not refer to Braunschweig marshalling yard, whose site specific accident statistics were used.

It is assumed for both rail and road traffic that the transports within the radius of 25 km each travel a distance of 50 km before they reach the waste disposal site. The frequencies of occurrence of transport accidents and the associated radiological consequences are calculated for this scenario. Consequently, the accident frequencies determined for the entire area within a radius of 25 km of the site represent upper bound values and cover specifically accident risks for any shorter transport distance in the region. In other words, if a certain frequency of transport accidents is anticipated for a traveling distance as a whole, the frequency for a part of this distance can under no circumstances be greater but must, in general terms, be lower. The anticipated frequencies of transport accidents cannot be less favourable at any location inside the 25 km radius than for the 25 km radius as a whole.

The same applies for other transport routes of similar length (50 km) in the Federal Republic of Germany since only a fraction of the total transport volume of radioactive waste passes along these routes when compared with the 25 km radius around the KONRAD installation.

With single-shift operation of the KONRAD waste repository, the annual transport volume is approx. 3,400 shipping units. A shipping unit is defined either as a cuboid con-

tainer or a pool pallet carrying one or two cylindrical containers. In the case of transportation by road, it is assumed that one unit is carried by the conveyance, owing to the weight of the shipping units. With rail transport, the shipping units are primarily transported by goods trains as part of standard goods traffic system, whereby one wagon carries two shipping units. The use of dedicated trains, comprising only wagons with waste containers, is assumed to be restricted to the carriage of waste derived from reprocessing of spent German fuel elements abroad.

The study initially looks at the component parts of transport accident analyses to determine the radioactivity released from the transport containers under different accident loads. In this connection, accident loads of transport vehicles and transport containers are divided into 9 severity categories in order to make adequate provision for the spectrum of possible accident impact. Because of the very different behaviour of various container types (concrete, cast iron, sheet steel containers) in conjunction with accident loads and varying waste forms (e.g. cement/concrete, bitumen) the transport volume is subsequently divided into different waste container classes. This categorization is determined primarily by release behaviour. Finally, depending on the previously defined severity categories and waste container classes, data are given on the fraction of the activity inventory (fractional release) released from the waste containers. In this context a distinction is made between tritium (H3), carbon (C14), halogens (e.g. iodine) and other radionuclides, owing to their varying release behaviour. Similarly, released aerosol particles are assigned to four particle size ranges on the basis of their aerodynamic diameter. The released activity of individual radionuclides, known as the source term, can then be determined from the fractional release, which indicates which fraction of the activity inventory of a waste container involved in an accident is released, and from the nuclide-specific activity inventory of the waste container.

Following the discussion of these features of accident risk analysis common to road and railway accidents, the study looks at accident frequencies.

8.2 Container Failure and Release Behaviour

Accident loads may fall within the performance standards provided for by the design or they may exceed them. In the present context, waste and transport containers are

designed primarily to satisfy the requirements specified in the "IAEA Regulations for the Safe Transport of Radioactive Material" as well as the design characteristics according to the "Waste Acceptance Requirements" derived from accident analyses for the operating phase of the KONRAD waste repository.

8.2.1 Definition of Severity Categories

As far as potential accidental consequences are concerned, the mechanical and/or thermal impact on the waste containers caused by the accident are of vital importance. Together with the properties of the waste containers and the form of waste they contain (e.g. cement/concrete, bitumen, compacted waste etc.), these determine the extent to which radioactive materials are released into the environment. A very broad range of accidental loads is possible in this connection, ranging from mild to very extensive mechanical impact onto the waste containers. In the case of fire incidents, which can occur on their own or in conjunction with mechanical container loads, the thermal energy input also varies within wide limits. This decisively influences the degree to which the waste product is heated and therefore also the extent of the release of radioactive materials; this thermal energy input depends on the duration of the fire, the way in which the waste container is exposed to the fire, and on the flame temperature. In combined events where a mechanical impact is followed by a fire, the release of radioactive substances is also influenced by the extent of prior mechanical damage.

To permit a quantitative evaluation of accident risks, the broad spectrum of possible accidental impacts must be condensed in a finite number of load categories, each of which in turn encompasses a wide range of possible effects on waste containers caused by accidents. For the purposes of the present study, nine severity categories were defined with the characteristics shown in Figure 8.1. The main variables of the breakdown are the "impact speed" and the "fire duration/temperature pattern", which determines the thermal energy input. Severity categories (BK) 1 (impact speed up to 35 km/h), 4 (impact speed between 36 and 80 km/h) and 7 (impact speed > 80 km/h) represent sequences of events producing only mechanical loads on the containers. In contrast, the other categories refer to accident situations where a fire incident also ensues. To keep the number of severity categories to a minimum, accidents in which a fire occurs on its own without a mechanical load are included in load categories 2 or 3

for combined mechanical and thermal impacts (impact speed > 35 km/h with subsequent fire).

impact velocity			
	without thermal impact	thermal impact 30 min., 800°C	thermal impact 60 min., 800°C
0 to 35 km/h	BK 1	BK 2	BK 3
36 to 80 km/h	BK 4	BK 5	BK 6
above 80 km/h	BK 7	BK 8	BK 9

Figures 8.1: Definition of the Nine Severity Categories

The speed at which the waste transport was travelling when the traffic accident occurred is used to determine the mechanical impact. A distinction is made between three speed ranges:

0 - 35 km/h

36 - 80 km/h and

> 80 km/h

In order to determine the fractional release, the waste containers concerned were assumed to impact against a hard, unyielding surface at the maximum speed of the relevant speed category. In conjunction with the speed range above 80 km/h, a speed of 110 km/h was assumed. In rare, extremely unfavourable individual scenarios, this model possibly underestimates the actual accidental impact. In the 0 to 35 km/h speed range, for instance, it is not impossible that heavy loads (such as the engine for instance) could fall on the transport container or that, in the event of a collision, a train travelling at a considerably higher travel speed could strike the container at a very unfortunate position. In such cases the energy input on the waste container could, in

certain circumstances, exceed that caused by an impact on an unyielding surface at 35 km/h. Effects exceeding those posited cannot be ruled out in the top speed category (assuming an impact at 110 km/h) either. In conjunction with risk determination, however, which involves consideration of a wide spectrum of accident constellations, the procedure is considered to be sufficiently cautious since individual incidents of this kind are largely equalized by the following conservative assumptions:

1. The use of the top speed in each velocity range rather than the mean value, for instance, generally results in a substantial overestimation of the accident speed.
2. A reduction of speed of the cargo before impact, as in the case of a wagon sliding after derailment, is not taken into account.
3. The assumed impact against a hard, unyielding surface such as solid bridge pile is likely to occur in reality only in exceptional circumstances; as a rule, the available surfaces are yielding or destructible, such as embankments or buildings.

The thermal impact is characterized by the fire duration/temperature pattern, assuming that the waste container is totally engulfed to fire. In defining the severity categories, the following conditions are assumed

No fire

30-minute fire at 800 °C

60-minute fire at 800 °C

Even in experiments conducted specifically for this purpose, fires corresponding to such dimensions (duration 30 or 60 minutes, temperature 800 °C, engulfing the transport container on all sides) can be simulated only with great difficulty, especially with large transport containers such as those used for waste transportation. In this respect, a specified fire load of even 30 minutes duration covers a high percentage of fire loads occurring in reality, and the 60-minute scenario allows for even extreme fire situations. A 30-minute fire at 800 °C corresponds to the reference fire to demonstrate compliance with the performance standards specified in transport regulations of the IAEA /IAE 85/ for Type B transport containers.

The severity classification scheme covers fires lasting for longer periods or burning at higher temperatures. Thus the transport container is exposed to higher temperatures by the fully engulfing 60-minute fire at 800 °C than by a fire lasting several hours within close proximity of the waste container, for example, such as could arise if nearby wagons or vehicles with a high fire load (heating oil, coal etc.) were to be consumed by fire in the accident.

A similar situation applies as regards the temperature. During stoichiometric combustion, flame temperatures in the hot temperature range generally lie considerably below the assumed value of 800°C. The generation of such temperatures is possible only in special configurations, e.g. welding torches. Investigations in conjunction with fire temperature determination reveal that average outdoor fire temperatures lie clearly below 800°C. Temperatures as high as this occur only in enclosed spaces with unfavourable thermal radiation geometry. However, these too are included in the heat transfer calculations by means of conservative assumptions so that, overall, higher waste product temperatures (and therefore releases) are calculated than experimentally observed. The conservative assumptions used with the heating-up time calculations, which form the basis of source term determination, include the following in particular:

1. Selection of conservative heat transfer parameters such as irradiation numbers, emission coefficients and heat transfer coefficients.
2. Disregard of insulating or shielding structures.
3. The cooling and insulating effects of any fire-extinguishing agents during the fire attack.

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

Overall, together with the stated boundary conditions (e.g. hard, unyielding impact surface, fire duration/temperature pattern with fully engulfing fire), the categorization scheme can be regarded as appropriate for the purpose of the study, which conservatively covers the broad spectrum of possible accidental impacts. This does not include theoretically conceivable extreme events, but these have such a low probability of oc-

currence that, as discussed below, they fall far short of the frequencies of occurrence that reasonably need to be considered.

8.2.2 Release Fractions

Accident-related releases of activity depend on the properties of the transport containers and the waste products they contain. For this reason, the range of waste containers in use is divided into waste container classes with the aim of categorizing waste containers with the similar release characteristics in a single group. In the following, a distinction is made between 8 waste container classes (AGG):

AGG 1 Bituminized waste in sheet steel cubical containers

AGG 2 Non-immobilized and non-compactable metallic and non-metallic waste in sheet steel cubical containers

AGG 3 Metallic waste in sheet steel cubical containers

AGG 4 Compacted waste in sheet steel cubical containers

AGG 5 Waste immobilized in cement in sheet steel cubical containers

AGG 6 Bituminized waste in concrete containers

AGG 7 Waste immobilized in cement in concrete containers

AGG 8 Waste in cast iron containers

The load-dependent fractional releases determined for these groups of waste containers are based on experiments and theoretical model calculations. The fractional releases forming the basis of the present study are presented in Tables 8.2.1 and 8.2.2. The values shown in Table 8.2.1 represent the airborne activity released in the form of aerosol particles for all radionuclides with the exception of tritium (H3), radiocarbon (C14) and halogens (e.g. iodine), for which values are listed in Table 8.2.2.

In the event of a mechanical impact on the waste container, aerosol particles with a large range of aerodynamic equivalent diameters (AED) can be released and become airborne. Particles with diameters < 10 µm AED are normally classified as fully respirable; particles with diameters > 10 µm AED are considered not to be respirable and therefore do not contribute to inhalation, although they may be part of radiation exposure via groundshine and food intake (ingestion). Particles larger than 10 µm have

higher deposition velocities, so that they can result in contamination of vegetation, ground and other surfaces in particular in the vicinity of the accident site.

The activity released during transport accidents is determined for the 8 waste container classes and 9 severity categories defined above for particles in the following size range intervals: 0 - 10 μm , 10 - 20 μm , 20 - 50 μm and 50 - 70 μm . To provide a clearer overview, the fractional releases for particles smaller than 10 μm are shown in Table 8.2.1 together with the compounded values for particles in the 10 - 70 μm size range. The values are specific for the airborne activity component released in the form of aerosol particles.

The information contained in the Table includes the following:

- In the purely mechanical load categories 1, 4 and 7, a clear increase from very low values to values in the 1 % range of fractional releases are observed.
- The design of the concrete and cast iron containers (Figure 3.1) prevents the release of radioactive material in some of the lower severity categories.
- As far as low mechanical loads are concerned, a comparison of the purely mechanical loads of category 1 with the combined mechanical and thermal loads of categories 2 and 3 indicates the dominance of the activity release caused by the thermal energy input. In the severity categories with impact speeds > 35 km/h plus fire, the fractional release amounts to 10 % of the activity inventory of the waste containers.
- In waste container class 1, which includes bituminized waste in sheet steel cubical containers, the release caused by fire is considerably higher than with waste immobilized in cement/concrete, for instance (AGG 5).

Much higher fractional releases are assumed for the H3 (tritium), C14 (carbon) and halogens (e.g. iodine) with thermal impact since these can take on a volatile form in the event of fire. Table 8.2.2 shows that complete release from the waste containers is assumed in most cases for the severity categories with fire (2, 3, 5, 6, 8 and 9) (fractional release = 1).

Fractional Releases of Radionuclides (other than H3, C14, Halogens) for Transport Containers from Accident Loads

Severity Category	AED / μm	AGG1	AGG2	AGG3	AGG4	AGG5	AGG6	AGG7	AGG8
1	0-10	8.9E-05	8.9E-05	8.9E-07	8.9E-07	6.5E-06	0.0E+00	0.0E+00	0.0E+00
	10-70	1.8E-04	1.8E-04	1.8E-06	1.8E-06	1.9E-04	0.0E+00	0.0E+00	0.0E+00
2	0-10	1.0E-01	1.3E-03	2.0E-04	4.0E-04	2.2E-04	0.0E+00	0.0E+00	1.1E-07
	10-70	1.8E-04	1.8E-04	1.8E-06	1.8E-06	1.9E-04	0.0E+00	0.0E+00	0.0E+00
3	0-10	1.0E-01	5.1E-03	4.0E-03	1.6E-03	5.1E-04	0.0E+00	0.0E+00	2.0E-05
	10-70	1.8E-04	1.8E-04	1.8E-06	1.8E-06	1.9E-04	0.0E+00	0.0E+00	0.0E+00
4	0-10	1.8E-03	1.8E-03	1.8E-05	1.8E-05	1.1E-04	0.0E+00	5.1E-05	0.0E+00
	10-70	3.5E-03	3.5E-03	3.5E-05	3.5E-05	2.4E-03	0.0E+00	1.2E-03	0.0E+00
5	0-10	1.0E-01	1.0E-01	2.2E-04	4.2E-04	2.9E-03	1.0E-01	1.4E-03	1.1E-07
	10-70	3.5E-03	3.5E-03	3.5E-05	3.5E-05	2.4E-03	0.0E+00	1.2E-03	0.0E+00
6	0-10	1.0E-01	1.0E-01	4.0E-03	1.6E-03	2.8E-03	1.0E-01	1.4E-03	2.0E-05
	10-70	3.5E-03	3.5E-03	3.5E-05	3.5E-05	2.4E-03	0.0E+00	1.2E-03	0.0E+00
7	0-10	5.4E-03	5.4E-03	5.4E-05	5.4E-05	3.2E-04	0.0E+00	1.6E-04	3.0E-08
	10-70	1.1E-02	1.1E-02	1.1E-04	1.1E-04	4.7E-03	0.0E+00	2.4E-03	0.0E+00
8	0-10	1.1E-01	1.1E-01	2.5E-04	4.5E-04	3.1E-03	1.0E-01	1.6E-03	2.2E-04
	10-70	1.1E-02	1.1E-02	1.1E-04	1.1E-04	4.7E-03	0.0E+00	2.4E-03	0.0E+00
9	0-10	1.1E-01	1.1E-01	4.1E-03	1.7E-03	3.1E-03	1.0E-01	1.6E-03	4.0E-03
	10-70	1.1E-02	1.1E-02	1.1E-04	1.1E-04	4.7E-03	0.0E+00	2.4E-03	0.0E+00

Table 8.2.1: Size dependent Fractional Releases for Particles of Aerodynamic Equivalent Diameter (AED) 0 – 10 and 10 – 70 μm for various Severity Categories and Waste Container Classes (AGG)

Fractional Releases of H3, C14 and Halogens for Transport Containers from Accident Loads

Severity Category	Nuklid	AGG1	AGG2	AGG3	AGG4	AGG5	AGG6	AGG7	AGG8
1	H3	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.
	C14	1	1	1	1	6.0E-02	0	0	7.3E-07
	Halogene					2.2E-04 5.0E-01			1.6E-04 1.6E-04
2	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	5.1E-04	1	1	6.0E-03
	Halogene					1	1	1	4.0E-02
3	H3	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.	w.s.N.
	C14	1	1	1	1	5.0E-01	0	0	4.0E-03
	Halogene					1	1	1	4.0E-02
4	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	5.1E-04	1	1	6.0E-03
	Halogene					1	1	1	4.0E-02
5	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	2.9E-03	1	1.4E-03	7.3E-07
	Halogene					1	1	1	1.6E-04 1.6E-04
6	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	2.8E-03	1	1	6.0E-03
	Halogene					1	1	1	4.0E-02
7	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	2.8E-03	1	1	6.0E-03
	Halogene					1	1	1	4.0E-02
8	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	5.4E-03 5.4E-01 5.4E-03	w.s.N.	w.s.N.	w.s.N.
	Halogene					1	1	1	7.3E-07 2.2E-04 5.0E-01
9	H3	1	1	1	1	5.0E-01	0	0	4.0E-03
	C14	1	1	1	1	3.1E-03	1	1	6.0E-03
	Halogene					1	1	1	4.0E-02

w. s. N. = as other Radionuclides

Table 8.2.2: Fractional Releases for Aerodynamic Equivalent Diameters of 0 – 10 μm for various Severity Categories and Waste Container Classes (AGG)

8.3 Accident Frequencies

A large body of accident data and statistics were assessed in order to ascertain the accident frequencies. These are detailed in the appendices (separate volume) to the present report. As far as transportation by road is concerned, some use was made of earlier investigations into accident frequencies and the extent of damage /PSE 85/ which have been updated by more recent data.

The accident statistics for road and rail transport contain information as to the frequency with which an accident must be anticipated per vehicle-kilometre driven or per goods train-kilometre (excluding minor damage), as well as a pro rata breakdown of accident events according to accidental impact (severity categories) with varying degrees of severity. Furthermore, a distinction is made as to the frequency of the number of wagons affected by accidents in the case of goods trains. This additional piece of information is essential for a meaningful application of the accident statistics to a particular transport volume since the accident frequency per goods train-kilometre alone does not give an insight into the accident probability of goods train wagons. In the case of the marshalling yards, the accident statistics refer to the number of accidents per 1 million marshalled goods train wagons and the relative frequency of different degrees of accident load (severity categories), as well as providing information on the numerical distribution of the wagons affected given an accident.

The following summary outlines the statistical accident database forming the basis of the analysis of the transport accident risk with waste transports to the waste storage site. The results are presented separately for transport accidents as part of railway goods traffic, marshalling operations and transportation by truck.

8.3.1 Accident Sequences and Accident Frequencies in Railway Goods Traffic

The transport volume of radioactive materials or only of radioactive waste by rail is too small to be used for statistical analysis. Consequently, it had first to be established whether the field of hazardous materials transportation by rail represented a suitable database. To this end, the reports of the Federal German Railways (DB) covering accidents and incidents relating to the transport of hazardous materials from 1981 to

1987 /DBB 87/ were evaluated. For each accident or incident, these reports contain a short description of what happened and details of the type of freight involved, the scope of damage, and the cause of the event. The evaluation showed that a large proportion of the incidents involving the transportation of hazardous materials is not representative for the subject under consideration here. For example, many incidents were caused by non-tight locks and seals and the resultant escape of hazardous liquids, something which is excluded in the transport of radioactive waste owing to the type of packaging and the waste material. Moreover, the statistical data for this type of transport was too limited to provide a reliable accident database. The investigation was therefore extended to cover the whole area of railway goods traffic, whereby the transport of hazardous materials is included as a subset.

Incidents in railway operations (accidents involving at least one moving railway vehicle) are systematically recorded by the DB for its entire railway network. Compilation of incidents is standardized by relevant rules of recording. The offices dealing with accidents have report sheets and instructions on their completion at their disposal. The data recorded in this way are collated and filed by the DB according to different aspects for further statistical evaluation.

In addition, an accident file is established for every accident and stored at the station with responsibility for the area in which the accident took place for a period of five years. Depending on the significance of the accident, this file contains more specific details on the incident than could be entered on the report sheets.

In conjunction with the present study, the "Survey of goods train accidents with material damage to vehicles of over DM 3,000 in the period 1979 through 1988" /DBB 88/ was evaluated. This database contains the date and station within whose area of responsibility the accident occurred for each accident in order to allow the incident to be identified; it also states code numbers for the type of event, type of train, the speed of the trains before the accident (except for fire incidents) and the estimated material damage to rolling stock.

A differentiation is made between the following principal types of railway accidents, whereby the code numbers permit an even more detailed breakdown:

- Derailment Occurs when a railway vehicle runs off or lifts off the track
- Collision Occurs when one railway vehicle impacts with another
- Impact Occurs when a railway vehicle runs against an obstacle in the track clearance, but not against another railway vehicle
- Crash Refers to an accident at a level-crossing involving a road user
- Fire/explosion Occuring in or caused by a moving railway vehicle

In the compilation of accidents /DBB 88/, an accident is categorized according to the type or primary cause of the event. The fire and explosion accidents constitute primary events. Fires or explosions occurring as a consequence of a prior mechanical accident, therefore, cannot be identified from this data base. Moreover, the compilation of accident data does not reveal such vital information as to the number of goods wagons affected in the accident.

Because the available documents were not sufficient to identify accidents in which fire resulted from another primary incident, and since they do not contain any data on the number of wagons affected by each accident, the DB carried out a survey specifically for these points in June 1989 at all stations with responsibility for areas in which goods train accidents with material damage to railway vehicles of over DM 3,000 occurred in the period 1983 to 1987 /DBB 89/. Data for the period before 1983 were no longer available at the time of the survey, and some documents were still being completed for 1988.

The objectives of the survey were to determine the fraction of accidents with mechanical effect and subsequent fire, and to obtain detailed data on the extent of damage to the individual wagons for all the documented accidents. In the period covered by the survey, a total of 292 accidents were recorded according to /DBB 88/. Additional details were provided for a total of 196 incidents /DBB 89/. These were, however, not always presented with the desired precision, so that conservative assumptions had to be made when determining the number of affected wagons in some cases.

The accident data compilation /DBB 88/ and the results of the special survey for the period from 1983 to 1987 constitute the primary data base evaluated and analysed for this study. This necessitated the classification of accidents in the severity categories

defined in Chapter 8.2.1. Goods train accidents are differentiated according to three speed categories (0 - 35 km/h, 36 - 80 km/h and > 80 km/h) on the basis of the travel speed recorded prior to the accident. All accidents contained in the data base with material damage to railway vehicles of over DM 3,000 were taken into account. If the damage caused is less than DM 3,000, the occurrence of a release in the event of the vehicle carrying waste containers can practically be ruled out. To ensure that the method is conservative, this relevance limit also covers incidents and associated impact which the waste containers can withstand without any difficulty. Also, the method of using the travel speed prior to the accident and the associated kinetic energy of the shipping units is conservative, and generally provides an upper limit for the accidental impact, in particular given that the impact is also assumed to be against an unyielding surface. Similarly, the subdivision of accident events into severity categories, each of which incorporates a wide range of mechanical and/or thermal loads, tends to result in overestimation of the accidental risk since it is assumed that the accidental load corresponds to that of the interval upper limit in each case when determining the accidental consequences. An accident occurring at 40 km/h, for instance, is classified in the 36 - 80 km/h speed range and treated like an accident at 80 km/h as far as the mechanical impact is concerned although the kinetic energy at the latter speed is four times as great.

The assignment of goods train accidents involving fire to the two categories of fire load defined in Chapter 8.2.1 is difficult without an in-depth analysis. The accident statistics also take accidents into account in which the fire was caused or supported by uncovered, readily flammable freight, by means of sparks or spontaneous combustion, for example. Such conditions do not exist with the containers used to transport radioactive waste. Nevertheless, fire incidents contained in the accident statistics are included in their entirety and, for the purpose of accident risk analysis, are categorized as fire accident equivalent to a fire duration/temperature pattern of either 30 minutes or 60 minutes at 800 °C fully engulfing the waste containers. In doing so, it is assumed that two out of three fires last for 30 minutes and that one out of three corresponds to the 60-minute reference fire. This classification clearly overestimates the real world conditions.

The data from /DBB 88/ summarized in Table 8.3.1 provide an overview of the accident frequency in railway goods traffic as a function of accident type and speed. The Table shows a numerical breakdown of the accidents involving goods trains occurring

between 1979 and 1988 according to the different accident types and speed ranges. The total goods train travel distance are also stated for the study period, thus allowing determination of the total accident frequency, an important element in accident risk analysis, of 0.34 goods train accidents per million train-kilometres. The statistics does not contain auxiliary exchange trains used to move goods wagons between consignors or recipients with private sidings to the next marshalling yard. Since the exchange trains travel primarily in areas with a comparatively high proportion of level crossings without barriers, their accident frequency is assumed to be increased. When the exchange trains are taken into account, the total accident frequency in goods train traffic rises to approximately 0.5 accidents per million goods train-kilometres.

Table 8.3.1 also shows that accidents with fire or explosion without prior mechanical impact account for approximately 8 % of the accidents that occur. Fires subsequent prior mechanical impact on the other hand are much rarer and occurred in the reference period of ten years in only three goods trains accidents (two accidents, in one of which two trains were affected by fire). With such a small number of incidents observed, albeit with potentially rather serious consequences, the possibility of a statistical fluctuation resulting in an underestimation of the accident frequency cannot be ruled out. The expected value of a probability distribution which allows the observed number of accidents being the lower limit of the 95 % confidence interval was therefore determined for the purposes of analyzing the accident risk of waste transports. In summary, this is more or less equivalent to doubling the assumed accident frequency of goods trains with a fire as a consequence of a prior mechanical effect.

Figure 8.3.1 also shows the pro rata breakdown of goods train accidents, derived from these accident data base according to the severity categories 1 to 9 posited in this study. The relative frequencies of the severity categories adds up to 1. Consequently, accidents with only mechanical impact are expected in approximately 89 % of all goods train accidents (load categories 1, 4 and 7). The remaining approximately 11 % are distributed among the six severity categories with combined mechanical and thermal loads. Fires without mechanical accidental impact were conservatively assigned to the < 35 km/h speed range. In assigning the total proportion of accidents with combined mechanical and thermal effect to speed categories, the same distribution was assumed as that determined from accidents with exclusively mechanical effect. It

Table 8.3.1 Number of goods trains involved in accidents (with material damage to railway vehicles of over DM 3,000 excluding exchange, work and auxiliary trains) from 1979 to 1988, grouped according to type of accident and speed range, as well as goods train-km travelled on the network of the Federal German Railways.

Type of accident	Speed (km/h)	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	Total 1979-88	Total 1983-87	Trains/ million km	Share ++)
Fire/explosion	0	8	5	5	8	3	6	4	6	4	3	52		0,027	8
	<35					0	0	2	0	0			2		
	Impact with sub-sequent fire					0	1	0	0	0			1		
	>80					0	0	0	0	0			0		
	Subtotal					0	1	2	0	0			3	0,003 +)	1 +)
Derailment	0 to 35	8	7	5	4	3	3	6	5	4	7	52		0,027	8
	36 to 80	14	8	11	4	8	3	2	3	14	0	67		0,035	10
	above 80	1	0	0	0	2	3	1	2	1	1	11		0,006	2
	Subtotal	23	15	16	8	13	9	9	10	19	8	130		0,068	20
Collision	0 to 35	22	21	20	12	10	15	16	11	8	6	141		0,074	21
	36 to 80	12	9	6	3	2	10	3	4	2	1	52		0,027	8
	above 80	0	0	1	0	0	0	0	0	0	0	1		0,001	0
	Subtotal	34	30	27	15	12	25	19	15	10	7	194		0,101	29
Impact	0 to 35	5	3	5	9	7	4	5	6	2	1	47		0,025	7
	36 to 80	8	11	19	16	7	15	9	18	3	7	113		0,059	17
	above 80	1	0	2	4	6	2	2	1	5	5	28		0,015	4
	Subtotal	14	14	26	29	20	21	16	25	10	13	188		0,098	28
Crash	0 to 35	1	1	1	0	0	0	1	1	0	0	5		0,003	1
	36 to 80	7	9	6	5	3	13	10	0	11	3	67		0,035	10
	above 80	1	0	1	4	1	0	2	2	4	2	17		0,009	3
	Subtotal	9	10	8	9	4	13	13	3	15	5	89		0,046	13
Total without fire	0 to 35	36	32	31	25	20	22	28	23	14	14	245		0,128	37
	36 to 80	41	37	42	28	20	41	24	25	30	11	299		0,156	45
	above 80	3	0	4	8	9	5	5	5	10	8	57		0,030	9
	Subtotal	80	69	77	61	49	68	57	53	54	33	601	281	0,314	91
	Total of all accidents	88	74	82	69	52	75	63	59	58	36	656	307	0,342	100
	Million train-km	201	200	197	187	178	189	197	194	187	186	1916	945		
+) Referred to the years 1983 to 1987															
++) Proportion of the particular accident category to all accidents (percentage of accidents with subsequent fire from 1983 - 1987)															
Further details in Section 8.3.1															

impact velocity	relative frequency					
	without thermal impact		thermal impact 30 min., 800°C		thermal impact 60 min., 800°C	
0 to 35 km/h	0,36	(BK 1)	5,9E-02	(BK 2)	2,9E-02	(BK 3)
36 to 80 km/h	0,45	(BK 4)	9,5E-03	(BK 5)	4,7E-03	(BK 6)
above 80 km/h	8,4E-02	(BK 7)	1,8E-03	(BK 8)	8,8E-04	(BK 9)

Figure 8.3.1: Relative Frequency of the Nine Severity Categories with Goods Train Accidents

is noticeable that fire incidents corresponding to a fire duration/temperature pattern of 30 minutes at 800 °C were assumed to occur twice as much as fire events lasting for 60 minutes.

The frequency of goods trains accidents and of the relative breakdown according to severity categories alone does not provide a sufficient basis for quantitatively evaluating the risk associated with transportation accidents for the considered transport volume. In many railway accidents, even when the relevance limit used here for the scope of damage is exceeded, the only damage is to the train engine. Particularly in accidents involving crashes at level-crossings, the large mass of the train engine, which is always at the front of goods trains, often prevents the goods wagons from being damaged by the accident. Other causes of accidents such as fire owing to malfunctions in the electric drive are confined exclusively to the train engine. Even in the most severe accidents, a large number of the wagons are often only slightly damaged if at all.

Quantitative information on the number of wagons affected in train accidents, depending on accident type and speed category, was derived from the data in /DBB 89/. A wagon was defined as being affected if the material damage incurred exceeded DM 3,000. Since appropriately detailed information was not available for all incidents, conservative estimates often had to be made as regards the number of wagons affected.

In connection with the number of affected wagons it could always be clearly ascertained whether any wagons at all, or only the power unit, were affected. In all the evaluated cases, at least an all-in figure indicating the number of affected wagons was available. In cases where the extent of damage to individual wagons was not otherwise stated, an upper limit for the number of affected wagons was specified in such a manner that the overall damage was not being exceeded, assuming damage of DM 3,000 to each affected wagon. Some instances of negligible damage were inevitably recorded as a result. The scope of damage to individual wagons was often described qualitatively. In such cases the wagons considered to be affected were those on which more serious damage to the structure and chassis could not be excluded. Where a list of the material damage to the individual wagons was available, the relevance limit of DM 3,000 was applied to each.

The results of the evaluation of primary interest for this study as regards the frequency with which a certain number of wagons is affected by the accident are represented in Figures 8.3.2 to 8.3.5. The graphs show the relative frequency with which a specified number of wagons is affected by an accident for the 0 - 35 km/h, 36 - 80 km/h and > 80 km/h speed ranges and for fires without prior mechanical impact. For incidents with "zero" wagons affected, the material damage is confined to the train engine or is below the relevance limit for wagons. It is evident that a high percentage of accidents - in some cases well over 50 % - fall into this category. This can be attributed to that fact that, by impacts (against obstacles) wagons are not seriously affected in over 80 % of occurrences; for crashes (at level crossings) this applies to over 90 % of occurrences.

In fires without mechanical impact, the most common incident is fire in the train engine, mostly caused by the electrical system. More than one-half of fire incidents are of this nature. It is also evident that even severe fires scarcely spread to the other wagons in the train in this accident category. Only one fire incident (without mechanical effect) was observed with two affected wagons. The same cannot be said to apply to fires that occur as a result of an accident with mechanical impact.

For 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 train engine is not the most frequent case.

The frequency distributions of affected wagons in goods train accidents (Figures 8.3.2 to 8.3.5) reflect the results derived from the accident analysis. Although gaps are found in the distribution of limited empirical data, which contain incidents with up to 14 relevantly affected wagons, a systematic pattern can be observed. In order to use the data in the risk analysis, the empirical data of affected wagons were fitted by means of distributions which satisfactorily describe the empirical distributions. The incidents in which no wagons (only the power unit) were affected were not included in the fitting procedure. The frequency of the occurrence of an accident with one to nine affected wagons, as well as for accidents with more than nine affected wagons, were determined from these distributions. Figure 8.3.6 summarizes the distributions adjusted to the empirical data for purely mechanical impacts and for fires not preceded by a mechanical load.

Accidental events where mechanical impact results in a subsequent fire were observed so rarely (two incidents with three train units affected by fire) that an empirical frequency distribution for the number of affected wagons is not defensible. This type of incident primarily comprises collisions (between railway vehicles) or derailments involving tank wagons with readily flammable materials. In this context it must be assumed that all the wagons which release flammable materials owing to mechanical impact or are carrying loose readily flammable cargo, are affected by fire. As far as these accident types are concerned there is a tendency for a greater number of wagons to be affected, whereby the fire will predominantly affect the wagons with the characteristics described above. In this context an uniform frequency distribution was assumed for incidents involving one to ten affected wagons for the purposes of the risk analysis. In summary, the assumption of an uniform distribution for incidents with up to ten affected wagons for each speed category were considered to be sufficiently conservative.

If the relative frequencies with which the various severity categories occur in the event of goods train accidents, as shown in Figure 8.3.1, are combined with the preceding information on the distribution of the number of affected wagons, the statistical data can be represented in the probability matrix reproduced in Table 8.3.2. The elements of the matrix indicate the percentage of goods train accidents involving accidental loads corresponding to the severity categories given in the first column and the number of affected wagons given in the first line. The values in the "0 wagons affected"

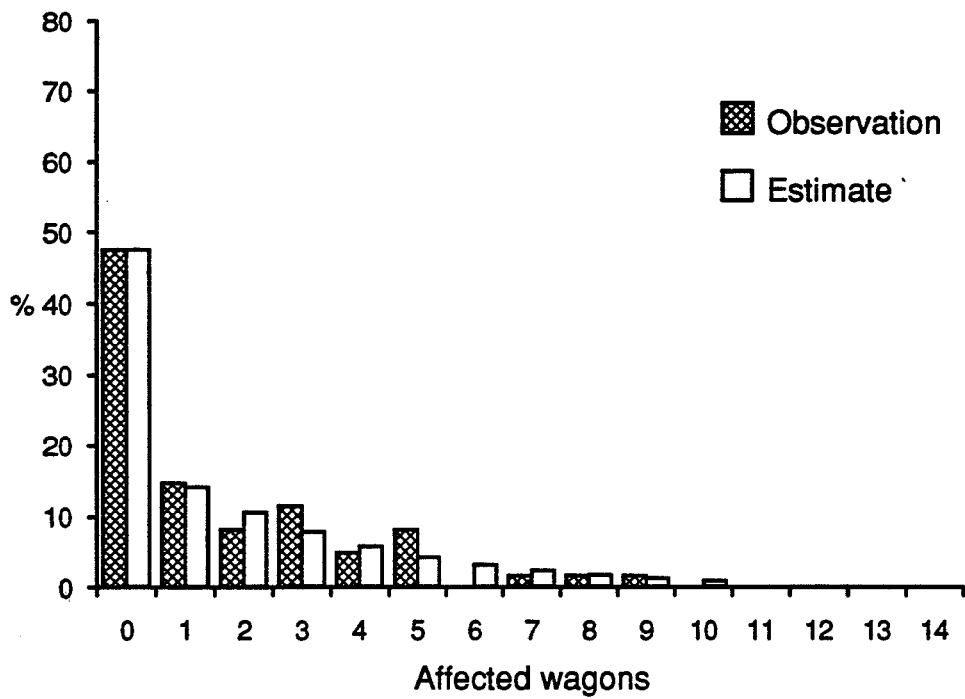


Figure 8.3.2 Relative frequency of a specified number of affected wagons in goods train accidents: speed range 0 to 35 km/h.

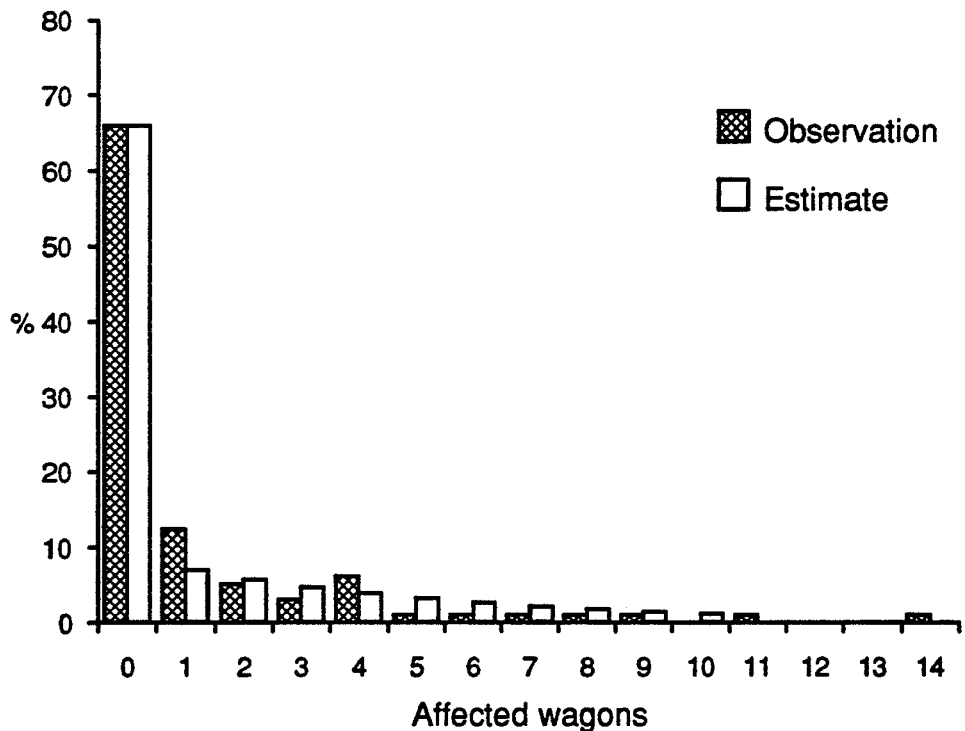


Figure 8.3.3 Relative frequency of a specified number of affected wagons in goods train accidents: speed range 36 to 80 km/h.

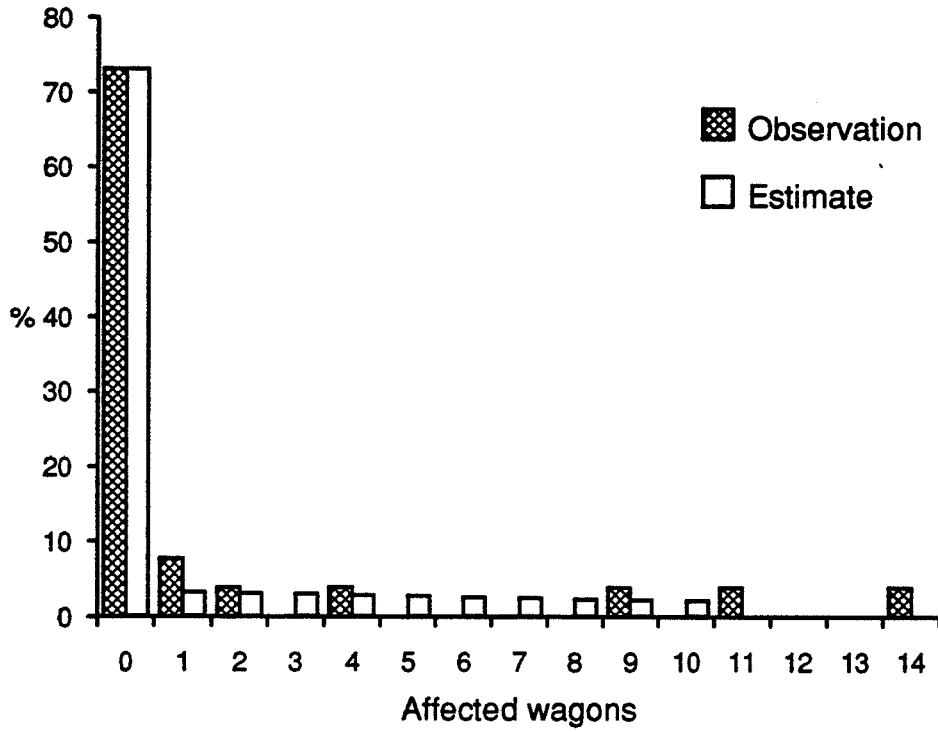


Figure 8.3.4 Relative frequency of a specified number of affected wagons in goods train accidents: speed range above 80 km/h.

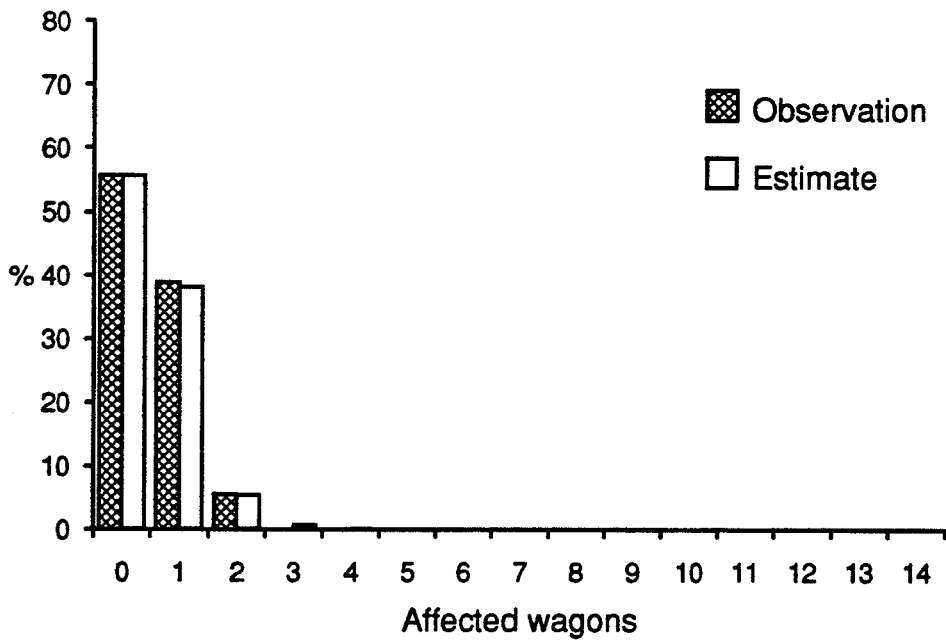


Figure 8.3.5 Relative frequency of a specified number of affected wagons in goods train accidents: fire without mechanical impact.

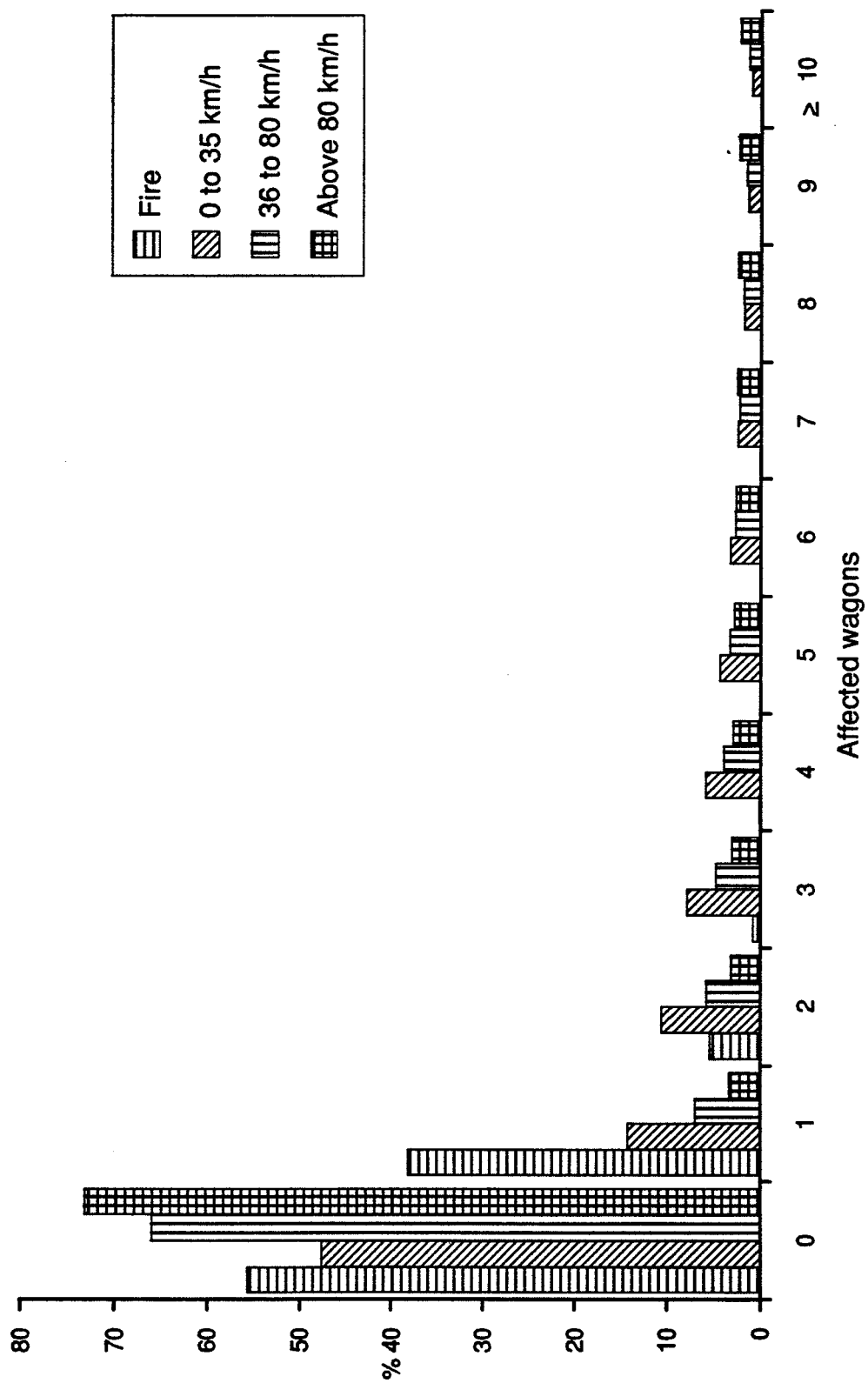


Figure 8.3.6 Relative frequency of a specified number of affected wagons in goods train accidents: estimated values

Table 8.3.2 Matrix of the probability of occurrence of a specified severity category and a specific number of affected wagons in goods train accidents (in %)

Severity categories	Number of affected wagons										Line totals	
	0 *)	1	2	3	4	5	6	7	8	9		≥ 10
0 to 35 km/h	17,09	5,12	3,80	2,82	2,09	1,55	1,15	0,86	0,64	0,47	0,35	36,0
0 to 35 km/h 800°C 30'	2,92	2,02	0,35	0,11	0,07	0,07	0,07	0,07	0,07	0,07	0,07	5,9
0 to 35 km/h 800°C 60'	1,46	1,01	0,17	0,05	0,04	0,03	0,03	0,03	0,03	0,03	0,03	2,9
36 to 80 km/h	29,77	3,15	2,60	2,14	1,77	1,46	1,20	0,99	0,82	0,68	0,55	45,1
36 to 80 km/h 800°C 30'	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,9
36 to 80 km/h 800°C 60'	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,5
Above 80 km/h	6,16	0,28	0,26	0,25	0,24	0,23	0,22	0,21	0,20	0,19	0,18	8,4
Above 80 km/h 800°C 30'	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,2
Above 80 km/h 800°C 60'	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 totals	57,55	11,74	7,34	5,53	4,36	3,50	2,83	2,31	1,91	1,59	1,34	100

*) e.g. only power unit affected

column refer to the train engine. The sum of this column is 58 %, i.e. accidental damage to the train engine above the relevance limit of DM 3,000 occurs in 58 % of all goods train accidents. The "10 wagons affected" column stands for ten or more affected wagons. The last column contains the line sub-totals of probabilities for the various accidental sequences. In this way, the fraction of the accidents accounted for by the different severity categories (load categories) already stated in Figure 8.3.1 are reproduced. The numerical values of the probability matrix clearly reveal the assumption that each configuration of affected wagons is uniformly distributed for the combined mechanical and thermal severity categories 5 and 6 as well as 8 and 9, in the absence of an adequate empirical data base. The sub-totals of the individual columns of affected wagons indicate that high numbers of wagons affected by accidents are increasingly improbable: in approx. 11.7 % of accidents only 1 wagon is affected, with two affected in approx. 7.3 % of cases; a total of ten or more were affected in approx. 1.3 % of accidents. These data, compiled for the purposes of the present transport risk analysis, were determined in a conservative manner.

Insofar as radioactive waste is transported to the waste disposal site by dedicated trains - as is the case with waste derived from reprocessing spent German fuel elements abroad - the values in Table 8.3.2 can be directly applied for the purposes of the accident analysis. For example, for accidents involving dedicated trains loaded exclusive with radioactive waste, the table immediately reveals the conditional probability given an accident being assignable to severity category 4 (mechanical impact, 36 - 80 km/h) and having 5 wagons affected by the accident. An accident with this outcome can be anticipated in approximately 1.5 % of all cases.

For all other waste transports which do not derive from reprocessing abroad, it is assumed, as explained in Chapter 5.2, that the waste is transported in mixed-cargo trains, that is to say as part of standard goods traffic.

Referred to the waste transports considered in this study, this means that the waste wagons are a component part of a larger train unit, either as individual or groups of wagons. In the event of a goods train accident, this affects the probability of wagons carrying radioactive waste being affected by the accident. In a mixed-cargo train carrying wagons with radioactive waste, the probability must be determined for wagons with radioactive waste being among the damaged wagons in a goods train accident with a specified number of wagons. Questions such as these can be answered

with the aid of combinatorial probability calculations. On the basis of statistical data, the average number of wagons carried by goods trains was set at 30. The analyses conducted in this connection are described in detail in the Appendix and used, among other things, to derive the accident probability per goods wagon-Kilometer from the information on the accident probability per train-km and the distribution of the affected wagons.

8.3.2 Operating Methods and Accident Frequencies at Braunschweig Marshalling Yard

Wagons carrying radioactive waste for the KONRAD waste disposal site are subject to marshalling if they are being shipped with standard goods traffic. Extensive research, which could not be extended to include a larger number of marshalling yards, was necessary in order to procure statistical accident data for marshalling operations. For this reason, the analysis of data has been concentrated on Braunschweig marshalling yard and is of particular interest in conjunction with the transport risk analysis owing to its location in the region the waste disposal site. Among other major marshalling yards, this installation has higher than average values as regards the number of marshalling accidents reported, compared to the number of wagons which undergo marshalling. Thus, the data specific for Braunschweig marshalling yard are required and represent conservative values for other marshalling yards.

The operating methods in the Braunschweig marshalling yard differ from those in other marshalling yards in that the wagons are mostly moved by utilizing the natural slope of the installation without a train engine. This applies both to the hump, from which the wagons are generally pushed one at a time (maximum of 4 axles simultaneously), and to the following tracks (sorting sidings, allocation tracks) on which also larger wagon groups, known as "groupings" (Nachlässe), are also moved by employing brake wagons. Speed limits of 5 km/h for pushing off the hump, 7.5 km/h for leaving the first retarder, 15 km/h on the approach speed when the drag block is applied, and 25 km/h for shunting gangs that operate with shunting power units are laid down.

The operational traffic consists almost exclusively of cargo wagons. Some 100 wagons per day are hazardous-cargo wagons, of which about 70 % carry flammable or

explosive material. For specially labelled hazardous cargo, gravity marshalling can be forbidden or is subject to special safety measures.

Typical accident sequences include insufficient coordination between those involved, defective drag blocks, mistakes in positioning the block, bumping, insufficient braking capacity when forming the "grouping", unsecured parking, non-compliance with speed limits or poor mass distribution in a set of wagons with high compressive forces in groups of wagons. Many of these accident sequences, however, generally result only in minimal damage.

Marshalling accidents in Braunschweig marshalling yard between 1987 and 1989 were evaluated according to the same relevance limit as that used for goods train accidents, that is material damage to railway vehicles in excess of DM 3,000. During the three-year period 17 relevant accidents occurred; compared to 2.28 million wagons marshalled on the hump 7.5 accidents therefore occurred per 1 million shunted wagons. Unlike the evaluation of goods train accidents, this number does not contain any cases in which only the train engine was affected.

As regards the accident types, the majority of accidents were caused by collisions and bumping (13 cases). Derailment and other causes were significantly rarer among the relevant accidents (4 cases). No relevant case of fire was recorded in the three years being considered. The personnel at the Braunschweig marshalling yard is not aware of any accident in which a fire resulted from mechanical impact of an accident, even prior to the period under investigation here.

When assigning the severity categories defined in Section 8.2.1, all the reported accidents were allocated to the mechanical impact category in the speed range < 35 km/h. While exact speed data are not available for any accident, because only train engine have a speed recorder, the detailed accident descriptions do lead to the conclusion that the upper limit of this speed range was not exceeded or rarely slightly exceeded. In addition, the accidental impact for most of these accidents is considerably overestimated within the framework of the risk analysis by positing an impact against an unyielding obstacle with a speed equivalent to the upper limit of the appropriate speed range. Any possible slight underestimation in an individual case is more than compensated for by this conservative procedure.

Even if none cases were observed at Braunschweig marshalling yard during the study period, the occurrence of accidents with fire during marshalling cannot be completely ruled out. It must be assumed that the frequency of fires is largely determined by the fraction of flammable or combustible cargo. Because the cargo in shunting operations comprises exactly the same material types as in goods train traffic, the risk analysis assumed that accidents with fire in shunting operations would be accounted for by the fraction observed in the regular goods train traffic. This supposition is conservative since some causes of fire that occur with goods train traffic do not exist or do not have the same importance for shunting operations. These include, for example, overheated axle bearings or brakes, or crashes at level crossings with (road) vehicles carrying flammable material in the form of fuel or cargo. The assumption posits one accident involving fire for 1.3 million (i.e. 0.8 per million) marshalled wagons. The two-to-one assignment to the half-hour and one-hour reference fires, respectively, was accordingly made as it was for regular goods train traffic.

As regards accidents with mechanical impact which result in subsequent fire, the fact that only low travel speeds generally apply in marshalling operations had again to be taken into account. Therefore, incidents with combined mechanical and thermal load were generally assigned to severity class 2 and 3, respectively, for safety analysis purposes.

As far as the number of wagons affected by an accident is concerned, most frequently only one wagon was affected, as with goods train accidents. The frequency with which several wagons are affected decreases even more rapidly with marshalling operations than with goods train traffic. No accidents with more than five affected wagons were observed. On average, therefore, fewer wagons were affected in a marshalling accident than was the case in en-route goods train accidents in the same speed range (0 to 35 km/h). This is primarily attributable to the fact that smaller sets of wagons or individual vehicles are usually involved in shunting accidents; similarly, fewer wagons are derailed at low speeds. The empirical distribution of the relative frequency for a specified number of wagons affected in marshalling accidents is illustrated in Figure 8.3.7.

For fire accidents and mechanical accidents with subsequent fire, the frequency distribution used for goods train accidents as regards the number of affected wagons was

also applied. In particular, an uniform distribution of the number of affected wagons for accidents with combined thermal and mechanical impact was conservatively assumed. However, the distribution was restricted to only up to five affected wagons in order to take account of the smaller average number of wagons affected in shunting accidents.

In line with the methods used with goods train accidents, the accident statistic for marshalling operations were summarized in a matrix of probabilities of occurrence and is reproduced in Table 8.3.3. In accordance with the frequency distribution for affected wagons described above, the columns for more than five affected wagons as well as the speed categories 36 to 80 km/h and above 80 km/h are not applicable. The empirical distribution was employed directly for the accidents in severity category 1 without fitting the data by means of a statistical distribution function. Consequently the field for three affected wagons remains empty in this severity category.

The fact that not all wagons affected in accidents carry radioactive waste has to be taken into account for the purposes of risk analysis as regards shunting operations as well. The relevant combinatorial statistics were therefore also applied for this case. A model had to be used as a basis for this, describing the frequency with which wagons carrying radioactive waste are present in a supposed accident environment. With due regard to the operational methods it seemed reasonable to suppose an accident environment comprising a train being assembled for further transportation to Beddingen interchange station. Such a train is characterized by a configuration of 30 wagons on average, with an equal distribution of the number of wagons carrying radioactive waste, up to nine, in accordance with the assumptions made for goods train traffic. In this way, the method developed for goods train traffic accidents could be applied analogously.

Table 8.3.3: Matrix of the probability of occurrence of a specified severity category and a specific number of affected wagons in shunting accidents (in %).

Severity categories	Number of affected wagons										Line totals
	1	2	3	4	5	6	7	8	9	10	
0 to 35 km/h	52,6	21,1	0,0	10,5	5,3	0,0	0,0	0,0	0,0	0,0	89,5
0 to 35 km/h 800°C 30'	4,8	1,0	0,5	0,4	0,4	0,0	0,0	0,0	0,0	0,0	7,1
0 to 35 km/h 800°C 60'	2,4	0,5	0,2	0,2	0,1	0,0	0,0	0,0	0,0	0,0	3,4
36 to 80 km/h	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
36 to 80 km/h 800°C 30'	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
36 to 80 km/h 800°C 60'	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Above 80 km/h	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Above 80 km/h 800°C 30'	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Above 80 km/h 800°C 60'	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Column totals	59,8	22,6	0,7	11,1	5,8	0,0	0,0	0,0	0,0	0,0	100,0

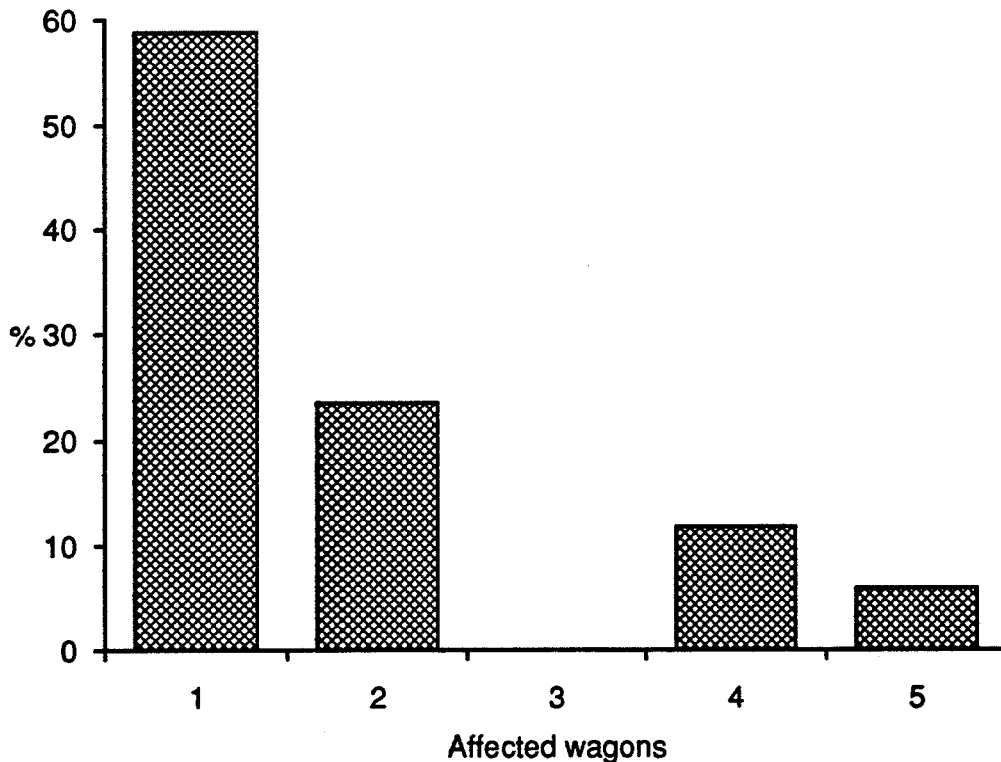


Figure 8.3.7 Relative frequency of a specific number of affected wagons in shunting accidents: empirical distribution Braunschweig marshalling yard 1987 to 1989

8.3.3 Accident Frequencies with Road Traffic

In determining accident frequencies for road transportation from statistical data, basic conditions must be stipulated which are comparable with the actual conditions in which the waste transports are effected. This refers to the characteristics of the transport vehicles and the transport routes relevant for describing potential accident environments. Owing to the weight of the planned shipping units, the vehicles used will generally be articulated lorries. As far as routing is concerned, transportation on motorways and - approaching the waste disposal site - on motorway-like main roads is both feasible and likely. These peripheral conditions were assumed when determining the accident frequencies according to Appendix III (see separate Volume).

The analysis of data was further restricted by disregarding accidents of heavy trucks with light vehicles (motorcycles, cars). There is evidence, that accidents of this kind generally do not affect on heavy trucks in such a way to cause damage to the load. Accidents causing material damage of less than DM 3,000 were also discounted from the accident analysis. This limit, which was determined from the available data, appears very conservative in comparison to the truly relevant effects, with the result that a large number of the accidents is included which almost certainly posed no threat to the freight.

Because of the resources available; only limited independent evaluations of primary data were possible. Consequently, the results of /PSE 85/ were used primarily as regards the relative frequency of certain accident types. These were supplemented by independent evaluations and other published results. The supplementary data refer primarily to assumptions regarding the breakdown of fire incidents between the two reference fires (800°C for 30 minutes and 800°C for 60 minutes) and the breakdown into accidents involving one or several vehicles. The frequency of flammable loads carried by the other party in the accident influences the frequency of the severity categories with thermal effect (fire).

The overall accident rate for articulated lorries on federal motorways was determined to be $3.5 \cdot 10^{-7}$ per km. The result is based on accidental data for 1987 and the percentage of the total mileage driven on motorways (53 %) from 1980. It can be assumed that these figures provide a reasonable description of the present situation.

The probabilities of occurrence determined for the individual severity categories are summarized in Figure 8.3.3. The relative probabilities add up to 1 (i.e. any accident that occurs is assigned to one of the specified severity categories). In almost 98 % of all accidents, purely mechanical impacts can be anticipated (sub-total of severity category 1, 4 and 7), with half of all accidents occurring in the speed range up to 35 km/h. Because of the speed limits applicable to heavy trucks, accidents occurring at a speed above 80 km/h are slightly less than 5 %.

A fire ensued in 2.3 % of cases. Of these, some 7.4 % satisfy the conditions of the 60-minute reference fire, while the remainder is covered by the 30-minute fire scenario. In comparison to the breakdown made for railway traffic these fractions are indicative for the conservatism included in the analysis where in the absence of an adequate database, one-third of accidents was assigned to the 60-minute reference fire and two-thirds to the 30-minute reference fire. The frequency distribution of fire accidents according to speed ranges deviates only slightly from the distribution for railway accidents with only mechanical impact. This indicates that accidents resulting in a fire without prior mechanical effect are rare in comparison to rail transport. Such type of accidents would result in higher frequencies in the 0 to 35 km/h speed range.

For road transportation, the data given in Figure 8.3.8 correspond directly to the matrix of probabilities of occurrence stated for rail transport accidents in Tables 8.3.2 and 8.3.3. The probabilities of occurrence in Figure 8.3.8 do present the input data for the accident simulation program described in Section 8.4.

impact velocity	relative frequency					
	without thermal impact		thermal impact 30 min., 800°C		thermal impact 60 min., 800°C	
0 to 35 km/h	0,4990	(BK 1)	1,1E-02	(BK 2)	8,4E-04	(BK 3)
36 to 80 km/h	0,4307	(BK 4)	9,5E-03	(BK 5)	7,6E-04	(BK 6)
above 80 km/h	4,8E-02	(BK 7)	1,1E-03	(BK 8)	8,4E-05	(BK 9)

Figures 8.3.8: Relative Frequency of the Nine Severity Categories for Road Transport Accidents

8.3.4 Representativeness of the Accident Data to the Region of the Repository

Investigations were carried out to establish the extent to which the available national data (old federal states) for accident frequencies can be transferred to the 25 km radius-region of the waste disposal site. The region being considered is too small to reveal significant deviations in regional accident statistics. This applies to rail traffic in particular. For this reason, the study relies essentially on a qualitative assessment of special regional characteristics relevant for indicating favourable or unfavourable deviations from national statistics.

As far as marshalling operations are concerned, the transport risk assessment is based directly on the accident data for Braunschweig marshalling yard where - disregarding Beddingen interchange station - the marshalling operations necessary in the vicinity of the waste disposal site will actually be carried out. There is therefore no need to examine these data's transferability.

Among other factors, the natural slope of the installation results in higher accident frequencies for this marshalling yard than the average of other major marshalling yards.

Additional marshalling operations become necessary at Beddingen interchange station when the waste wagons are delivered in mixed-cargo trains. These are controlled by VPS. As in Braunschweig, they are generally effected on the hump. However, at the site there is no natural slope that could make accidents more likely to occur. According to VPS, wagons carrying radioactive waste and marked with hazardous goods labels, would not be marshalled over the hump. The same applies to wagons already combined to form groups, a scenario likely to occur frequently with waste wagons as a result of prior marshalling in Braunschweig. Avoiding the hump, such wagons will be forwarded on tracks controlled by signals directly to the sorting siding track by using a train engine. Movements of this kind within the marshalling yard are subject to a speed limit of 25 km/h. The track system inside the marshalling area is much smaller and more clearly laid out than in Braunschweig, and the supervision of the generally much lower marshalling volume by a small number of people reduces the chance of accidents, e.g. because of insufficient coordination between shunting personnel, which is the cause of a large number of shunting accidents and incidents. Another way of averting coordination problems is to conduct the marshalling operations under remote control, whereby the driver of the train engine assumes direct supervision of the other operating procedures.

As regards its technical equipment and operating procedures, the features with relevance to safety for operations under VPS control are equivalent to those of the Federal German Railways. This is supported by information provided by VPS indicating that in the past 10 years no incidents have been recorded with operating procedures such as those anticipated here. On the whole, therefore, it can be reasonably assumed that the accident risk referred to the number of wagons marshalled in Beddingen interchange station will be smaller than that for Braunschweig marshalling yard.

Currently available information on waste transport in the region of the waste disposal site, the Hannover-Braunschweig route of the DB-network in particular will be affected by the waste movements. The route linking Vöhrum and the Braunschweig marshalling yard is located within a radius of 25 km of the waste disposal site. Other routes likely to be used include Braunschweig-Helmstedt (depending on the future waste disposal concept for the new federal states) and, to a lesser extent, Hildesheim-

Braunschweig, which coincides with the Hannover-Braunschweig route after Gross-Gleidingen.

Neither the current accident data, insofar as they refer to this region, nor the information available on aspects of routing relevant for safety or route construction give any indication that the accident risk on these routes will be any greater than on the national average. The fraction of single-track routes within the 25 km zone surrounding the site likely to be used for waste transportation (18 % from Hoheneggelsen to Gross-Gleidingen), for instance, which can be assumed to entail a higher accidental risk, is with 34 % clearly below the value of 54 % for the network of Federal Railways prior to the accession of the GDR (referred to the length of line operated). Moreover, the relevant route is expected only to be used for waste transportation on a small scale. With 0.57 crossings per Kilometer, the number of level crossings within the 25 km zone is also lower than the average of 0.76 crossings per km for the nationwide network of Federal Railways. Route characteristics potentially favouring accidents (e.g. narrow curve radii) or characteristics that could aggravate the accident consequences (e.g. major drops) are largely avoided by the topographical features of the area, which is generally flat.

Reorganization of the traffic volume as a result of increasing traffic in the new federal states are rather speculative. However, there are indications suggesting that an improved route structure with enhanced safety will be achieved as a result of this development in the medium term.

As far as the safety standards of the operating stock and the management practices are concerned, an equivalent safety standard to that of the Federal German Railways can be anticipated for transports by VPS from Beddingen interchange station to the waste disposal site. The speed limit of 40 km/h applicable to the entire VPS network considerably reduces the potential accident loads in most conceivable accident scenarios. Thus the risk for this transport route is certainly overestimated by using the data of the goods train traffic of the Federal German Railways.

As far as road transportation is concerned, the location of the waste disposal site allows the waste to be shipped almost exclusively on federal motorways with the exception of a short, well-developed road section within the immediate vicinity of the site. For this reason, the accident frequency of the relevant vehicle types on motorways

was taken as the basis for determining the transport risk. The level of development of these routes is up to standard, so that the road conditions cannot be expected to give rise to less favourable conditions than the national average. On the contrary, the topographical situation of the region is such that hazardous features such as steep inclines and winding stretches are not present. The same applies as with rail traffic as regards sections that can aggravate the consequences of an accident, such as major drops, for example.

It can generally be concluded that there are no indications to call the transferability of the basic accident data to the region around the site into question. There are indications suggesting that the application of national data to the waste disposal site region may result in an overestimation of the transport risks.

8.4 Transport Accident Simulation - Source Term Definition

In the event of a transport accident, several influencing variables determine the extent to which radioactive substances are potentially released:

- The magnitude of the mechanical and thermal impact acting on shipping units with radioactive waste as a result of the accident. Nine load categories are defined in this connection.
- The number of shipping units affected by the accident. This depends on the number of shipping units per vehicle being transported and, in the case of railway transport on the number of waste wagons affected.
- The waste container and waste product properties (8 waste container classes) and the radioactive inventory of the shipping units affected by the accident determine the radioactivity released as a result of the accident.

An accident simulation program was used to describe the spectrum of possible accident sequences and the potential releases of radioactive substances, also taking the anticipated frequency of the events into account. The program takes into account the transport volume (217 reference waste types and their relative frequency), different transport constellations as regards the number of waste wagons in the goods train and their load, the possible accident severity (9 categories) and, on this basis, produ-

ces a large number of source terms which are representative for possible releases of radionuclides as a result of accidents. Likewise the frequency of such releases can be determined. The conservative assumptions explained in the previous chapters for establishing values that determine the release from waste containers and frequencies of accident impact are an integral part of the simulation program.

A brief explanation is provided below of how the individual shipments of radioactive waste by rail and road are modeled in the simulation program, and of how transport accidents are simulated and a sufficiently large number of source terms is determined so as representatively to cover the transport volume and accident spectrum. In this connection, the following aspects of railway goods traffic, marshalling operations and road transportation are discussed:

- Loading of transport vehicles
- Simulation of transport accidents
- Determination of released activity

8.4.1 Waste Transportation by Rail

- Loading of waste wagons

The following assumptions are made for transportation by rail:

- Two shipping units are carried per cargo-wagon.
- Waste derived from reprocessing German fuel elements abroad is shipped by dedicated trains comprising 20 cargo-wagons, each carrying 2 shipping units.
- Waste originating from other sources is shipped by regular goods trains, that is to say in "mixed-cargo trains". It is assumed in connection with the region of the waste disposal site, in which waste wagons from different originators are carried more frequently by one goods train following marshalling operations, that the train carries 1, 2, 3 etc. up to a maximum of 9 such wagons with the same frequency. The maximum value is consistent with disposal capacity of the waste repository of a maximum of 17 to 18 shipping units per day with single-shift operation.

- Waste containers are disposed of in groups with the same external dimensions (disposal container class according to Table 3.1) a goods train carries uniform waste container types.

According to these specifications, standard goods trains with waste wagons carry 5 such wagons and a total of 10 shipping units on average, compared with 20 wagons and a total of 40 shipping units carried by dedicated trains. With an annual storage capacity of 3,400 shipping units, and bearing in mind that approx. 52 % of these (cf. Figure 3.2) are derived from reprocessing, the following transport volume can be anticipated in the region of the waste disposal site for the 100% rail transportation scenario:

- 44 dedicated trains
- 164 standard goods trains.

As far as standard goods trains are concerned, the average number of cargo wagons carried per train is taken as 30 on the basis of statistics from the German Federal Railways.

Reformation of trains such as those at Braunschweig marshalling yard result in standard goods trains frequently carrying waste shipments from different consignors. Compared with transportation on a national scale, this results in a smaller number of standard goods trains; however, on average these carry more waste wagons. Outside the region of the waste disposal site, it is assumed that a larger number of goods trains will carry a correspondingly lower average number of wagons as was the case when determining the radiation exposure from regular transportation. These suppositions influence the results of the study only very slightly, if at all.

The statistical data on the relative frequency of different accident severities and the number of affected wagons summarized in Table 8.3.2 also include events in which up to 10 wagons are affected by an accident. As a result of the previous assumptions on loads of dedicated trains and standard goods trains, the simulation program simulates accidents in which 1, 2, and up to a maximum of 10 wagons with radioactive containers are affected. The frequency of occurrence of such events is also taken in-

to account in each case; for high accidental loads and a large number of affected wagons these are accordingly low (cf. Table 8.3.2).

A shipment of radioactive packages is modeled by "Monte-Carlo" simulation, a statistical procedure enabling different constellations to be generated on the basis of statistical data. The simulation process is shown schematically in Figure 8.4.1.

The first stage involves determining whether the simulated transport is by means of a dedicated train or a mixed-cargo train.

Then the disposal container class must be determined in each case. In this context, the frequency distribution of different waste container types is taken into account, such as represented in Figure 3.3. All the waste containers in a simulated transport belong to the same disposal container class to reflect the procedure of disposing of similar container types.

The number of wagons is specified as 20 for dedicated trains; for mixed-cargo trains the number (n_{wag}) is determined at random from the range 1, 2, 3 ... 9.

This is followed by a loop which is passed through n times ($n = n_{wag}$) for mixed-cargo trains and 20 times for the dedicated trains, in order to generate the shipment of the train.

In this context, the waste originator is determined for each wagon, taking into account the volume of shipping units provided for disposal of the selected disposal container class. In other words, the frequency with which a waste originator is represented in this process is consistent with the proportion of the waste transport volume of the previously determined disposal container class provided by the waste originator. In connection with dedicated trains, the only possible originators are COGEMA and BNFL; with mixed-cargo trains all other originators are considered.

Finally, waste types (reference waste) are assigned to the two shipping units in each wagon. In this context cumulative frequency distributions of different reference waste types are available for each waste originator and each disposal container class, derived from the waste database compiled by the Federal Office for Radiation Protection (BfS).

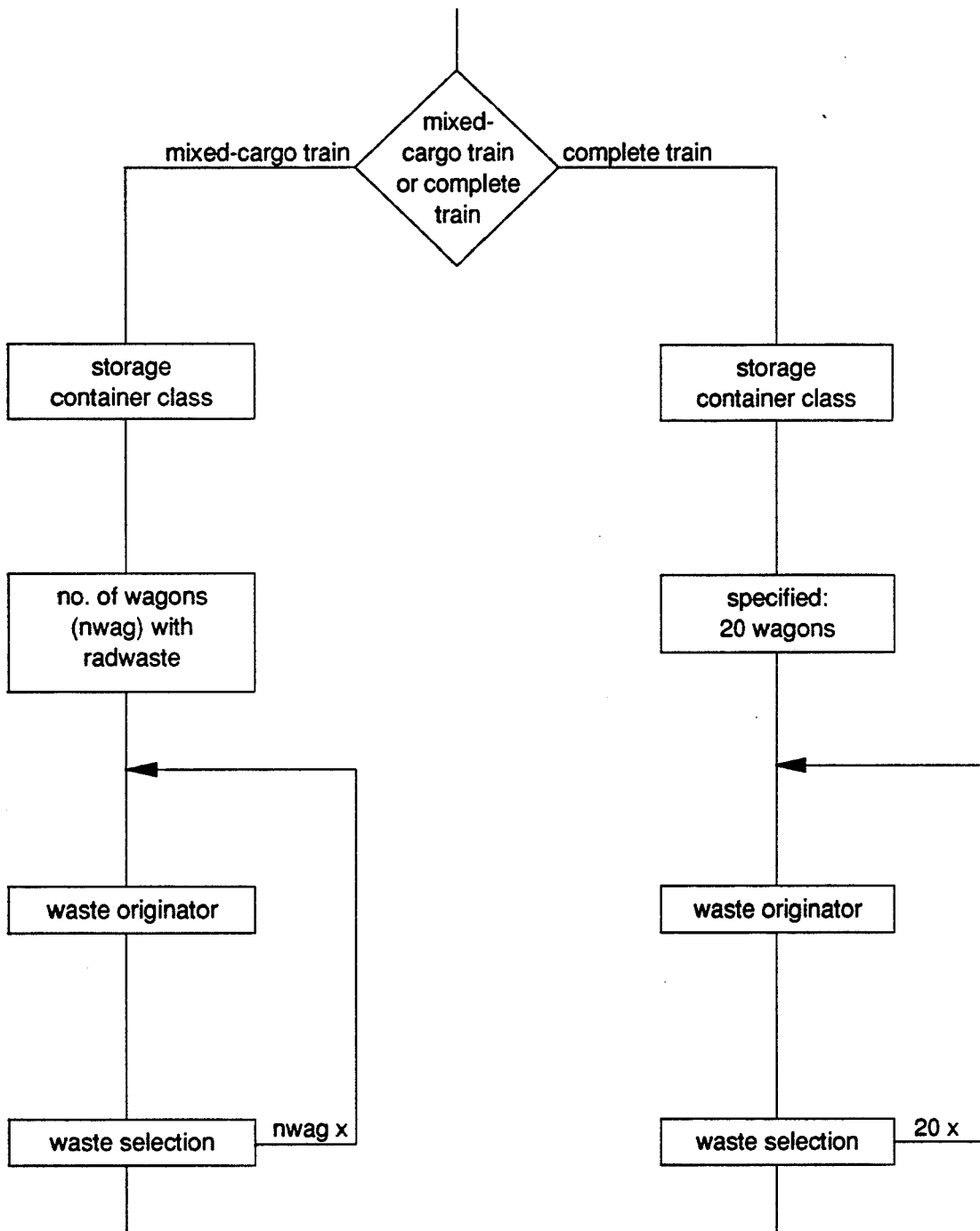


Figure 8.4.1: Structure of the Simulation Model for Waste Transportation by Rail

- Simulation of transport accidents

The procedure for simulating accidental sequences in order to determine the entire range of potential consequences with their probabilities of occurrence is elucidated for railway goods traffic in Figure 8.4.2. The procedure enables 500 different consignment configurations of goods trains, such as described above with the aid of Figure 8.4.1, to be simulated separately for each of the 9 severity categories. The number of wagons (n_{wag}) carrying radioactive waste packages is set to 20 for dedicated trains; with mixed-cargo trains n_{wag} assumes values of 1, 2, 3 etc. up to 9 with equal probability. Railway accidents can result in 1, 2, 3 etc. waste wagons being affected, where by accidents with up to 10 affected wagons are taken into account in accordance with Table 8.3.2. However, these accidental sequences occur with differing probability. As explained in Chapter 8.3.1, these relative frequencies can be read off directly from Table 8.3.2 for dedicated trains depending on the severity category. In the case of mixed-cargo trains these probabilities further depend on the number of waste wagons (n_{wag}) in the total of 30 goods wagons being carried in the train.

The process for assigning two shipping units of a specific category for each wagon leads to a consecutively numbered quantity n_{wag} (≤ 9 in mixed-cargo trains, 20 in complete trains) of loaded waste wagons. The simulation program now generates source terms for accidental events for waste wagon 1, waste wagons 1 and 2, waste wagons 1, 2 and 3 etc. being affected by the accidents for the specified severity category. This procedure is continued for dedicated trains until a source term is created where 10 waste wagons are being accidentally affected.

With mixed-cargo trains, the procedure is continued until a source term for n_{wag} (≤ 9) affected waste wagons is calculated. At the same time - assuming a railway accident - the conditional probability of the relevant accident sequence, and of the associated source term, is stored. The severity category is also stored since a distinction must be made according to whether the release does or does not involve fire for the purpose of subsequently calculating atmospheric dispersion and the potential radiation expo-

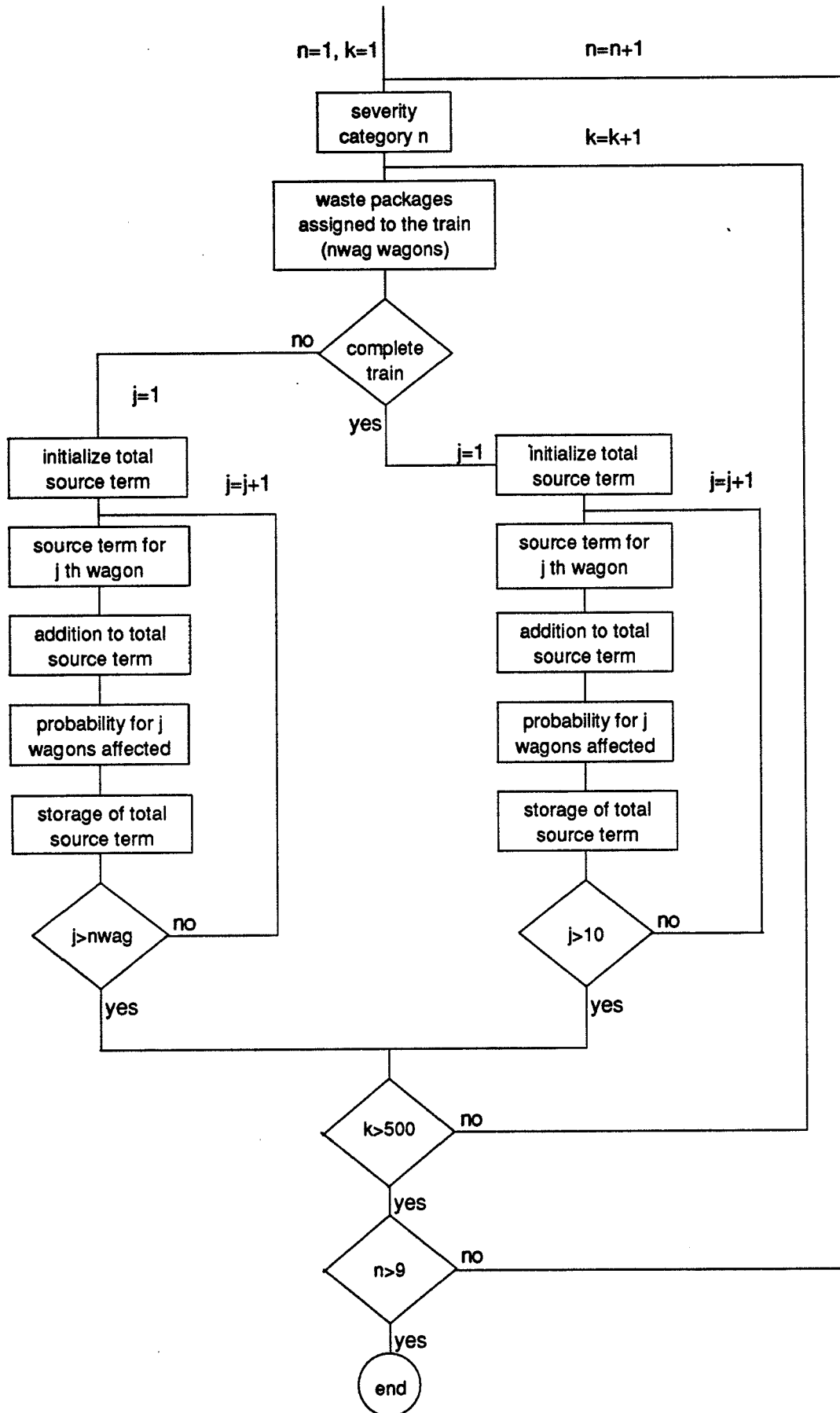


Figure 8.4.2: Simulation of Accidents with Railway Goods Traffic

sure. Thus, for each simulated shipping configuration, a total of 10 source terms is generated for dedicated trains, and n_{wag} source terms (the number of previously determined wagons with radioactive waste) are generated for mixed-cargo trains. In this connection, accident sequences are also registered in which the waste containers withstand the accidental forces (cf. Table 8.2.1) and no release of radioactive substances takes place. With 500 consignment configurations for each severity category the procedure illustrated in Figure 8.4.2 leads to a total of approx. 27,000 generated source terms ($9 \cdot 500 \cdot [0.21 \cdot 10 + 0.79 \cdot 5]$) which represent the spectrum of possible releases in the event of goods train accidents.

8.4.2 Waste Transportation by Road Transport Vehicles

Because of the size and weight of the shipping units, it is assumed that one shipping unit is carried on an articulated lorry when radioactive waste is transported by road. To simulate shipments on road transport vehicles, accident loads and resultant source terms, the procedure is similar to that described in Figures 8.4.1 and 8.4.2 with the simplification that only one vehicle and one shipping unit is affected by the accident. In determining the type of consignment, the selection is made from all consignors, taking the entire volume of reference waste types into consideration, with the exception of waste derived from reprocessing abroad which is assumed throughout this study to be transported by rail.

Irrespective of the relative fraction in the accident spectrum, 500 consignments with one shipping unit are generated for each of the 9 severity categories. The released activity of individual radionuclides (source term) is determined for each simulated consignment and, at the same time, the relative frequency of the severity category considered is also recorded (assuming an accident occurs, cf. Figure 8.3.3). A total of 4,500 ($=9 \cdot 500$) source terms, representing the spectrum of potential releases in the event of road transport accidents, was generated.

8.4.3 Braunschweig Marshalling Yard

Wagon loadings, accident loads and subsequent source terms are simulated in exactly the same way for marshalling accidents as in the procedures described in Chapter 8.4.1, with the following modifications:

- As far as the loads carried by goods wagons are concerned, all reference waste types are considered apart from the waste from reprocessing returned to Germany from abroad, which is assumed to be transported by dedicated trains and directed straight to the waste disposal site without passing through Braunschweig marshalling yard.
- In line with the evaluation of shunting accidents at Braunschweig marshalling yard described in Chapter 8.3.2 (cf. Table 8.3.2), only accident events in severity categories 1 to 3 involving up to 5 wagons are considered.

As with accident in railway goods traffic, the simulation program generates goods train consignments with up to 9 waste wagons travelling in a train of 30 wagons, for which marshalling accidents are simulated with up to 5 affected wagons for 3 possible load categories according to Figure 8.4.2. This produces a total of around 5,800 source terms ($500 \cdot 3 \cdot 35/9$) each with its conditional probability of occurrence (assuming a marshalling accident occurs). These represent the spectrum of potential releases in the event of marshalling accidents.

8.4.4 Formation of Source Term Groups

A source term generated by the accident simulation program represents the released activities of individual radionuclides with the simulated accident configuration. These radionuclide-specific activities are determined by the activity content of the waste package involved in the accident and the fraction assumed to be released into the atmosphere according to Table 8.2.1 and 8.2.2 with the accident load (severity category) and waste container group concerned. As described in Chapter 8.2.2 and Appendices IV and V, a distinction is made between four particle size ranges of aerodynamic equivalent particle diameter (AED) (0-10 μm , 10-20 μm , 20-40 μm and 40-70 μm) so that one source term comprises four sub-source terms. For the purpose of subsequent analysis of possible radiological consequences and their probabilities of occurrence, the following additional information is assigned to each source term:

- The severity category ($k = 1, 2, 3 \dots 9$)
- The conditional probability of occurrence (assuming an accident occurs)
- A radiological hazard index calculated from the radionuclide specific activity which permits an approximate relative classification of different source terms with respect to the potential radiological consequences.

The radiological hazard index of a source term is calculated by summation of the activity of the various radionuclides multiplied by the nuclide-specific weighting factors. The weighting factors used are considered to be an adequate measure of the relative radiological significance of the individual radionuclides subsequent accidental releases.

To facilitate the analysis of environmental consequences, the large number of simulated source terms must be grouped in a limited number of representative source terms, designated as release categories. Consolidation of source terms to representative release categories is conducted separately for railway, marshalling yard and road transport accidents.

In doing so 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 and thermal load categories. Source term groups are then formed by combining accidental sequences with approximately equal hazard indices. The average representative source terms - known as release categories - were determined by taking the probability of occurrence of the individual (simulated) accidental sequences into account. For assigning individual source terms to source term groups the cumulative probabilities of occurrence were specified separately for transport accidents with purely mechanical and combined mechanical/thermal accidental load characteristics. The cumulative probabilities were according to the subsequent table specified in a way that the range of values of hazard indices of accidental sequences having high hazard indices did not differ substantially. This procedure is intended to assure representativeness particularly for the source terms resulting in higher radiological consequences.

Source term group	Cumulative probability
1	0.5
2	0.4
3	0.095
4	0.0045
5	5.0E-04

This procedure also accounts for the relative probability of occurrence for each source term group, provided the accident takes place.

The individual source terms combined in a source term group on the basis of their radiological hazard index, can be assigned to very different conditional probabilities of occurrence, depending on which simulated accident event (e.g severity category, number of affected wagons) is considered. The conditional probabilities of occurrence of individual source terms in a source term group are taken into account when forming a release category representative for the source term group by means of appropriate weighting. In this way a representative composition of the radionuclide-specific activities of the release category is obtained. In other words, source terms having a higher probability of occurrence are more important in forming the source term group, i.e. the composition and quantity of radionuclides, than others.

8.4.5 Release Categories

The simulation of potential accidents from transporting waste to the Konrad repository results subsequent grouping and consolidating of numerous generated source terms in various release categories which are representative with respect to the composition and quantity of radionuclides considered to be important for radiological assessment purposes. For accidents involving transportation by goods trains, road vehicles and at Braunschweig marshalling yard, 10 such release categories are generated by the accident simulation program for each mode of transport. In this context, release categories 1 to 5 are derived from accidents with purely mechanical impact on shipping units, while release categories 6 to 10 represent accidents with mechanical impact and subsequent fire.

- Goods train accidents

Figure 8.4.3 shows the released activity of the radionuclides H 3, Co 60, Sr 90, Cs 137, Pu 238, Pu 241 for the 10 representative release categories (FK 1 to FK 10) for goods train accidents. The selection of the radionuclides listed in Figure 8.4.3 allows for the fact that these radionuclides are of particular importance either by their activity content in the waste and/or their radiological significance. The information on the released activity of the listed radionuclides refers to the total activity released in the particle size range from 0 - 70 µm AED.

It is apparent that the released activity goes up markedly as the numbers increase for release categories derived both from purely mechanical accident impact (FK 1 to FK 5) and from combined mechanical and thermal accident impact (FK 6 to FK 10) (logarithmic scale). This is in contrast to the conditional probabilities of occurrence also shown in the figure. These state the relative frequency with which the individual release categories occur, given a goods train accident resulting in the release of radioactive material. The conditional probabilities of occurrence of the 10 release categories therefore total 1. Releases caused by an accident which correspond to release category FK 1, for instance, occur with a conditional probability of 0.38; this contrasts with the very low probability of occurrence of $4.8 \cdot 10^{-7}$ for release category FK 5 with its comparatively high activity releases. The absolute probabilities of occurrence of these release categories are calculated from the probability of an accident associated with the release of radioactive substances, multiplied by the conditional probability (assuming an accident with release occurs) of the release category concerned.

- Road transport accidents

Figure 8.4.4 shows the released activity (0 - 70 µm) of the selected radionuclides H 3, Co 60, Sr 90, Cs 137, Pu 238, Pu 241 for the 10 representative release categories (FK 1 to FK 10) for road transport accidents. The released activity with source term FK 1 (without fire) and FK 6 (with fire), which can be anticipated more frequently, are shown to lie in a comparatively low range. Releases caused by accidents

of this kind can be expected in approx. 50 % (48 % + 1.9 %) of all releases associated with heavy goods vehicle accidents, as indicated by the conditional probabilities of occurrence (assuming an release associated accident occurs) of the release categories, which are also shown. The activity releases of the release categories with higher numbers, such as FK 4 and FK 5 (without fire) and FK 9 and FK 10 (with fire), on the other hand, are orders of magnitude higher. These source terms result from accidents occurring less frequently and/or accidents in which waste packages with a very high activity inventory are involved. The conditional probabilities of occurrence derived from the accident analysis, for example, of $4.1 \cdot 10^{-3}$ for release category FK 4 or $1.6 \cdot 10^{-4}$ for release category FK 9 suggest that correspondingly high releases must be anticipated in one accident out of 250, or in one accident out of approximately 6,000 respectively. However, in this context, reference is made in particular to the comments at the end of Chapter 8.5.1.

A comparison of Figures 8.4.3 and 8.4.4 reveals that the released activities with goods train accidents are higher on average than with accidents involving trucks. This is to be expected, since a truck carries only one shipping unit at a time, compared with two shipping units in the case of a goods wagon. Furthermore, the simulation of goods train accidents also includes events in which up to 9 waste wagons are affected by the accident. The fact that this difference is only marginally visible when the release categories are compared by the mode of transport can be attributed to the fact that the waste containers reveal a very different activity inventory (cf. Figure 4.3) when several wagons are affected by an accident. As a result, only a few affected shipping units determine the size of the release.

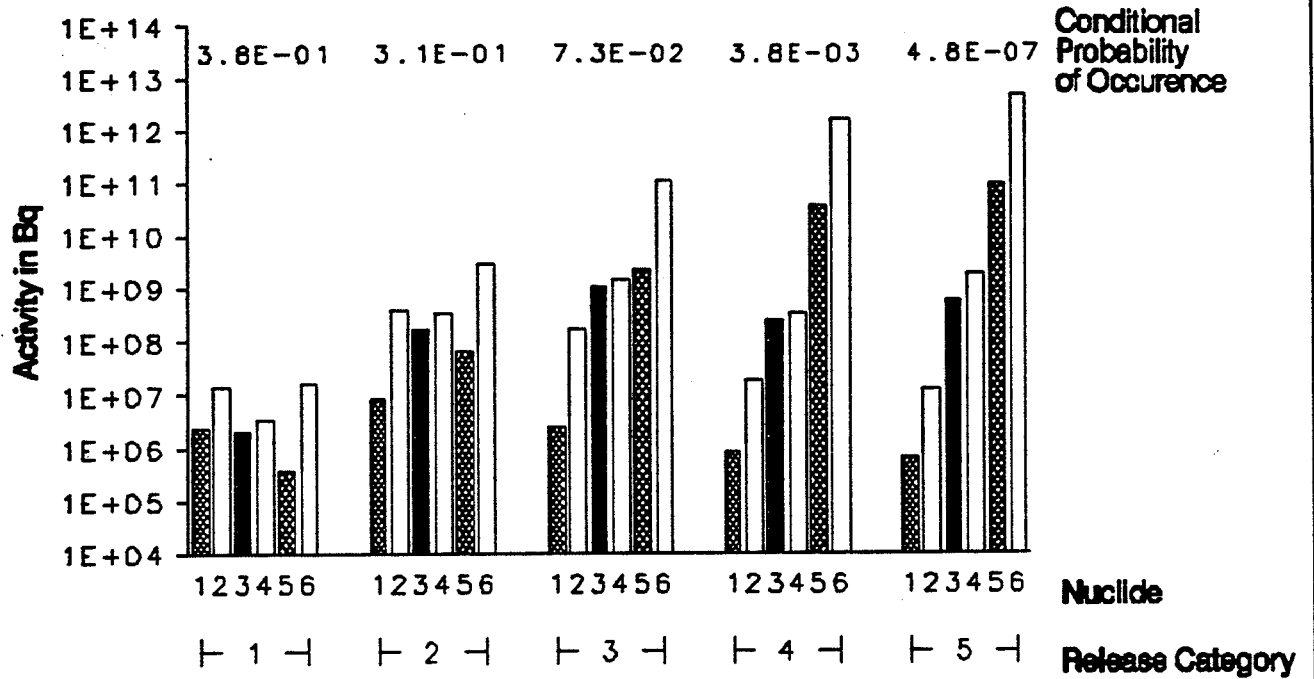
- Marshalling accidents

Similarly Figure 8.4.5 shows the released activities for selected radionuclides with the release categories representative for accidents at Braunschweig marshalling yard. A comparison with Figures 8.4.3 and 8.4.4 reveals that marshalling accidents with and without fire do generally occur in a speed range that is conservatively covered by assuming a mechanical load corresponding to 35 km/h impact on an unyielded surface.

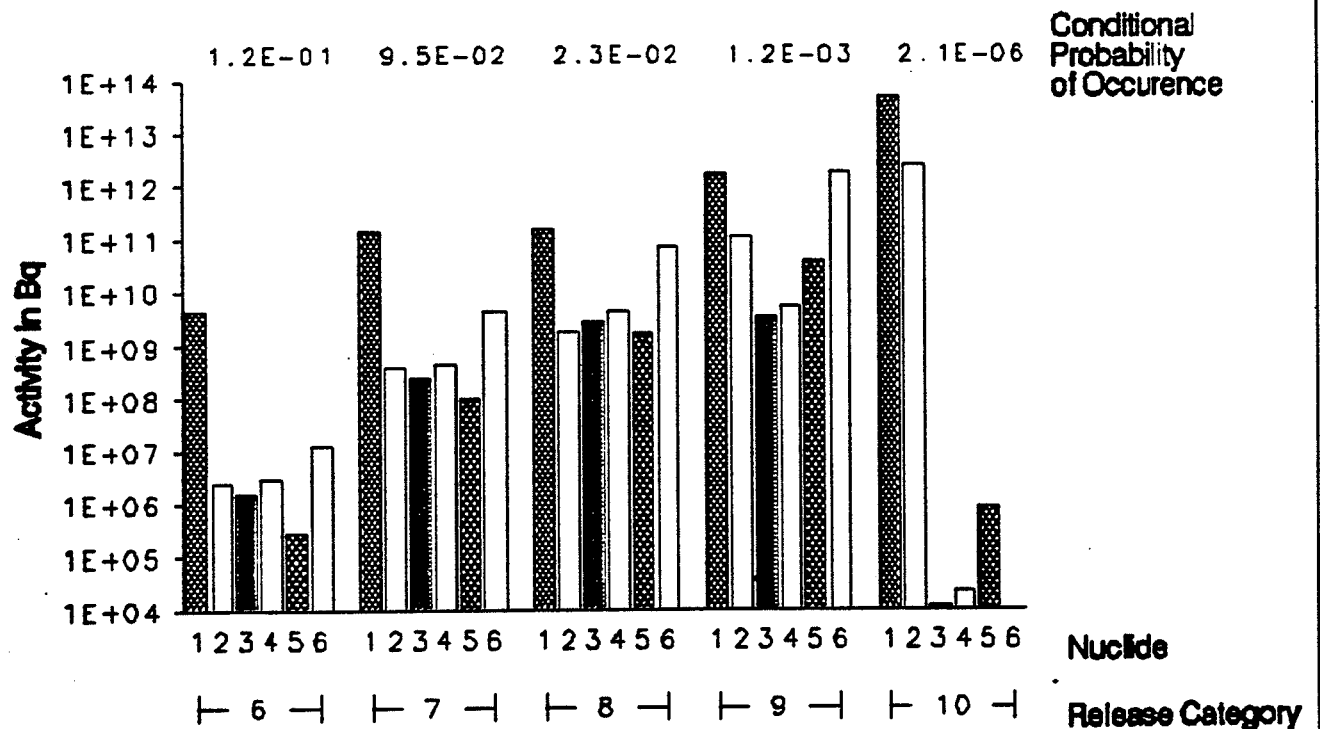
Potential Activity Releases subsequent Train Accidents

Scenario: 100% Rail Transport

Accidents without Fire



Accidents with Fire



1=H 3
4=Cs137

2=Co 60
5=Pu238

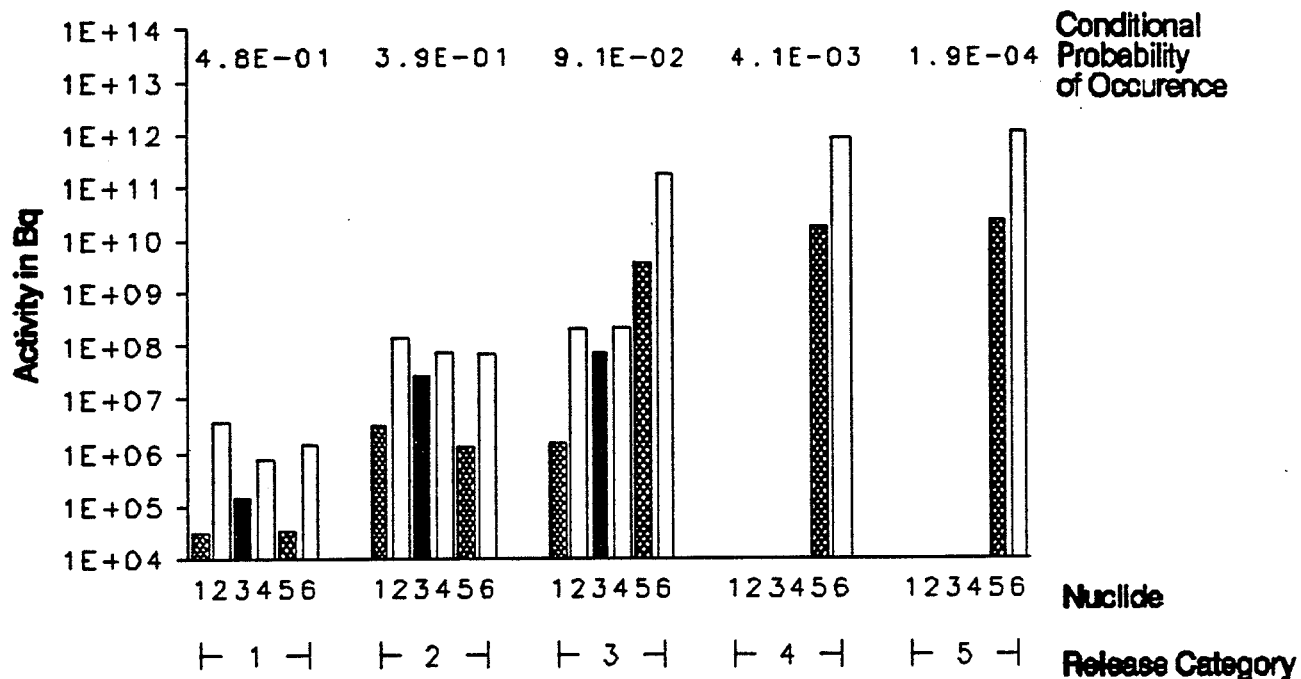
3=Sr 90
6=Pu241

Figures 8.4.3

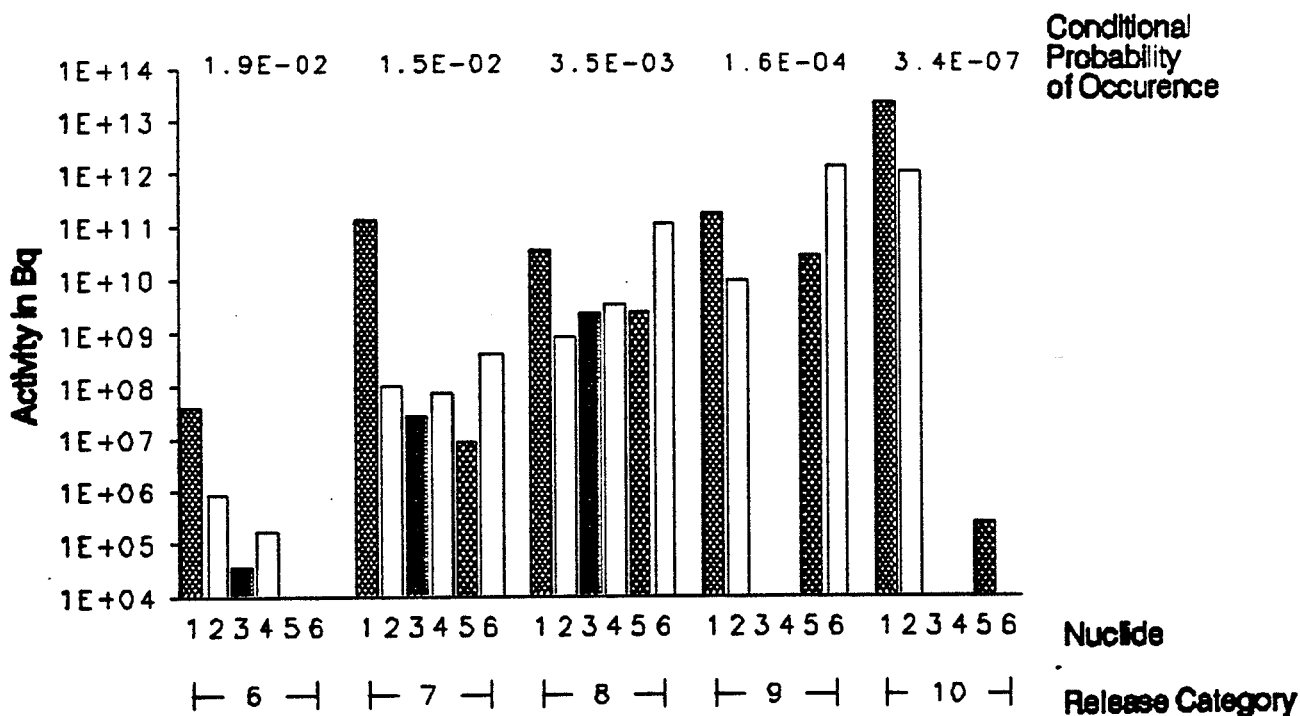
Potential Activity Releases subsequent Road Accidents

Basis: Reprocessing Waste excluded

Accidents without Fire



Accidents with Fire



1=H 3
4=Cs 137

2=Co 60
5=Pu 238

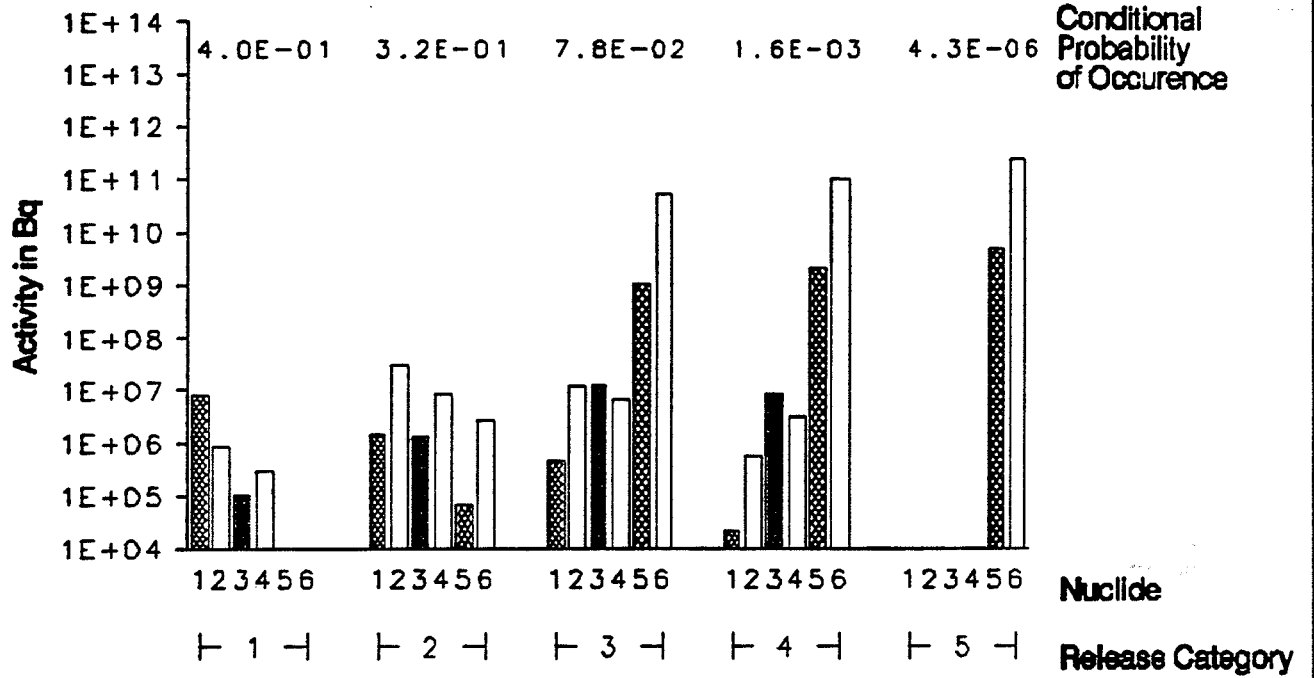
3=Sr 90
6=Pu 241

Figures 8.4.4

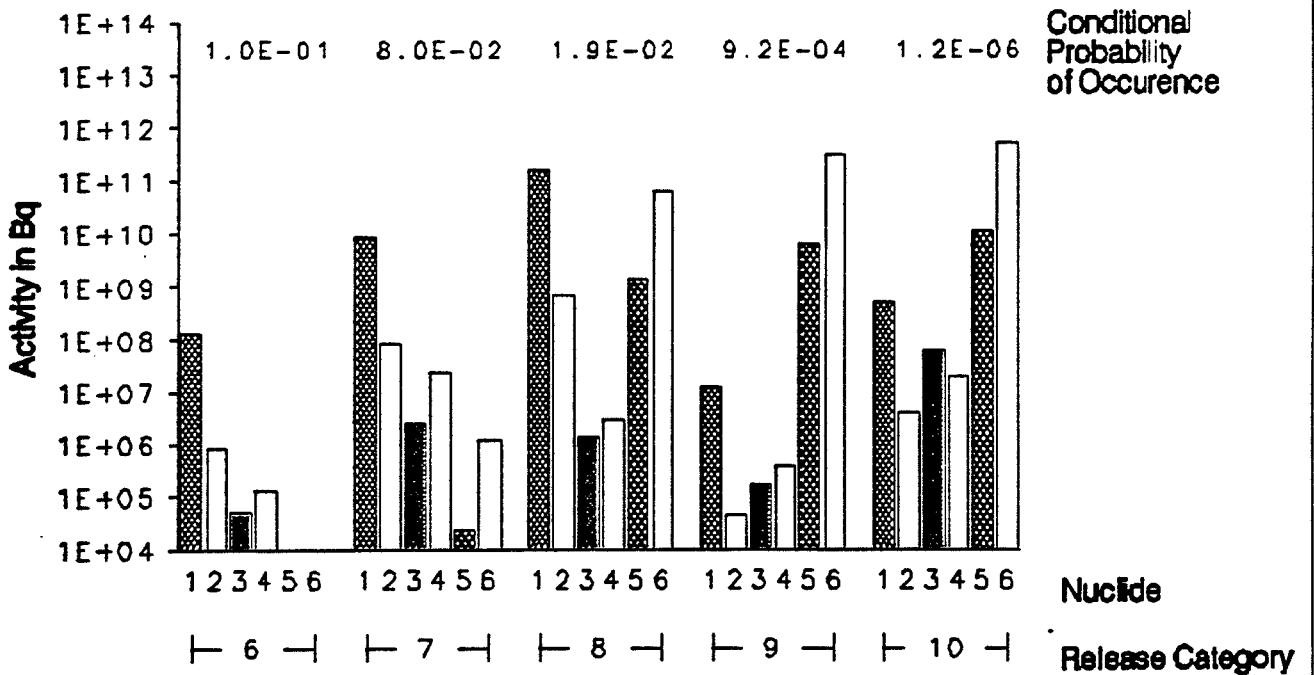
Potential Activity Releases subsequent Marshalling Accidents

Basis: Reprocessing Waste excluded

Accidents without Fire



Accidents with Fire



1=H 3
4=Cs 137

2=Co 60
5=Pu 238

3=Sr 90
6=Pu 241

Figures 8.4.5

The absence of higher severity categories becomes apparent in particular with the higher release categories and associated lower activity releases.

8.5 Expected Accident Frequencies with Release

The simulation of consignments of shipping units and of possible accident loads, to which the vehicles and their loads could be subject to results initially in a large number of source terms which are then grouped into release categories; these constitute representative releases for transport accidents given the transport volume to the KONRAD waste disposal site under consideration here. Releases caused by accidents in railway goods traffic, at Braunschweig marshalling yard and during transportation by road are covered by 10 release categories for each case, five representing mechanical and five representing combined mechanical and thermal loads on shipping units. Each of these release categories are assigned with the conditional probability of its occurrence assuming an accident in which shipping units carrying radioactive waste are affected and resulting in a release of radioactive substances.

In order to evaluate the risks associated with the transportation of radioactive waste to the KONRAD waste disposal site, the expected frequencies of accidents with a release must be determined so that the expected frequencies can be assigned to the individual release categories. Referred to one year's waste transport volume, these state the frequency with which releases caused by accidents and represented by a release category, can be anticipated. These expected frequencies are developed in the following chapters for accidents associated with railway goods traffic, operations at Braunschweig marshalling yard, and road transportation.

8.5.1 Railway Transport

The frequency must be determined with which accidents resulting in a release of radioactive material from waste containers can be anticipated in the region of the waste disposal site, assuming the annual delivery of 3,400 shipping units by goods trains (100 % rail transport). The expected frequency will be determined (cf. Chapter 8.1) for a radius of 25 km around the planned KONRAD waste disposal site. As discussed in Chapter 8.4.1, the following annual transport volume will be anticipated in the vicinity of the waste disposal site for the 100% rail transportation scenario:

- 44 dedicated train comprising 20 wagons, each carrying 2 shipping units
- 164 regular goods trains, comprising 30 wagons on average, of which, with equal frequency, 1, 2, 3 ... 9 waste wagons are loaded with 2 shipping units.

These specific assumption do not significantly influence the accident frequencies stated below since the accident frequency per waste wagon is independent of the number of waste wagons being carried in a train. However, to make sure that accidental events in which a large number of waste wagons may be affected by a train accident are also included by the simulation process - with correspondingly high releases -, the aforementioned is generally justified and plausible assumptions are taken as starting point.

The result is the following:

The average route length within the 25 km region of the waste disposal site is assumed to be 50 km for both regular goods trains and dedicated trains. According to Chapter 8.3.1, a total accident frequency of 0.5 train accidents per million kilometres can be anticipated for railway goods traffic. Therefore, the annual frequency with which railway accidents can be anticipated within a 25 km radius by 208 goods trains (164 + 44) carrying radioactive waste is as follows:

$$208 \frac{\text{Trains}}{\text{a}} \cdot 50 \text{ km} \cdot 0.5 \cdot 10^{-6} \frac{\text{Accidents}}{\text{Train} \cdot \text{km}} = 5,2 \cdot 10^{-3} \frac{\text{Train accidents}}{\text{a}}$$

In other words, assuming continuous operation of the waste repository, a goods train carrying wagons with radioactive waste containers would be anticipated to become involved in an accident once in approx. 190 years on average.

As discussed in detail in Chapter 8.3.1, the occurrence of a train accident does not necessarily affect wagons with specific characteristics - such as waste wagons. For only a fraction of train accidents one or several of the waste wagons being carried will be affected. In the case of dedicated trains carrying exclusively waste wagons, the only train accidents involving no waste wagons are such in which only the power unit is affected. According to Table 8.3.2, this is the case in some 58 % of goods train accidents. Therefore, in 42 % of train accidents waste wagons will be affected as well. This percentage is smaller with mixed-cargo trains since railway accidents that involve goods wagons, but not necessarily waste wagons, can also occur. Taking the accident data of Table 8.3.2 and the general conditions of mixed-cargo trains carrying 30

wagons on average including, with equal frequency, 1, 2, 3 ... up to 9 waste wagons, it can be concluded that in approx. 18 % of all accidents involving mixed-cargo trains one or more waste wagons will be affected. These data result in the following overall fraction of goods train accidents in which at least one waste wagon is affected:

$$\frac{44}{208} \cdot 0.42 + \frac{162}{208} \cdot 0.18 = 0.23$$

In other words, assuming that an accident involving a train that is carrying a waste wagon takes place in the vicinity of the waste disposal site, a waste wagon can be expected to be affected in 23 % of cases. Therefore, considering the waste transport volume of one year, a railway accident in which one or more waste wagons are affected must be anticipated somewhere inside the 25 km radius region with a annual frequency of $1.2 \cdot 10^{-3} \text{ a}^{-1}$ ($5.2 \cdot 10^{-3} \text{ accidents/a} \cdot 0.23$). This is to say that such an event would be anticipated every 830 years on average in the hypothetical case of continuous operation of the waste repository.

If a waste wagon is affected by an accident so that waste containers are subject to a load according to one of the 9 severity categories, this does not lead to a release of radioactive substances in every case. The data compiled in Table 8.2.1 as regards release fractions with accident loads indicate that concrete and cast iron containers can withstand the accident effects in some of the lower accident categories, so that no release of radioactive material is to be expected. Taking the relative frequency of different waste container groups in the total transport volume into account on the one hand and the severity categories (cf. Figure 8.3.1) on the other, it can be shown that no release of radioactive substances occurs in 42 % of all train accidents where at least one waste wagon is affected. This value is calculated by the accident simulation program which, when simulating a large number of load and accident constellations, also registers events in which no release of radioactive substances occurs. In conjunction with the numerical data above, this indicates that train accidents associated with a radioactive release can be anticipated with a annual frequency of $1.2 \cdot 10^{-3} \text{ a}^{-1} \cdot (1 - 0.42) = 7.0 \cdot 10^{-4}$ per year for the 100 % rail transport scenario. Given the hypothetical continuous operation of the waste disposal site, a train accident involving a release of radioactive material from waste packages could be expected to occur approx. every 1,400 years on average. In this context note that both the quantity released and the radiological significance can vary within wide limits.

Several components of the accident risk analysis, such as the definition of the severity categories, the frequency of severity categories and establishment of release fractions associated with different severity categories, give a result indicating that a release of radioactive materials occurs in roughly half (58 %) of all train accidents in which a waste wagon is affected. This percentage is undoubtedly far too high and can be attributed to an accumulation of a series of conservative assumptions made within the framework of the present accident risk analysis. These include:

- When evaluating accident statistics, a goods wagon is considered to be affected, if the material damage exceeds DM 3,000.
- The speed of the train before the accident determines the speed range (0 - 35 km/h, 36 - 80 km/h, > 80 km/h) to be used for assigning the accident severity.
- The accident load of the goods wagons is taken to be equivalent to the accident load of 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 the same as an impact at 35 km/h, for example, which has an energy effect that is 50 times greater. Furthermore, it is assumed that the waste package impacts against a surface corresponding to an unyielding 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 and heavy waste containers.
- The fact that the shipping units are carried in multiple-axle, comparatively rigid goods wagons that are closed on all sides is not taken into account.

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

8.5.2 Road Transport

In the 20 % road/80 % rail transport scenario, it is assumed that 20 % of the shipping units are transported to the waste disposal site by articulated lorries each carrying one shipping unit. As explained in Chapter 8.4.2, all reference waste types are considered as potential loads with the exception of waste being returned from reprocessing abroad. With a total number of shipping units of 3,400 per year, 20 % of deliveries corresponds to 680 truck loads per year. As stated in Chapter 8.3.3 the accident frequency of articulated lorries on federal motorways and main roads amounts to 0.35 accidents per 1 million km. The average distance travelled when driving to the waste disposal site within a 25 km radius zone is assumed to be 50 km. Therefore, the accident frequency for the transport volume carried by road transport vehicles in one year is calculated as follows:

$$680 \frac{\text{Trucks}}{\text{a}} \cdot 50\text{km} \cdot 0.35 \cdot 10^{-6} \frac{\text{Accidents}}{\text{km}} = 1.2 \cdot 10^{-2} \frac{\text{Accidents}}{\text{a}}$$

In other words, assuming continuous operation of the waste repository, an accident in which the shipping unit is affected can be anticipated to occur once in approximately 80 years somewhere on the roads used within a 25 km radius zone of the waste disposal site. Since the concrete and cast iron containers used comparatively frequently (cf. waste container groups 6, 7 and 8 in Table 8.2.1) are able to withstand the accidental loads in some of the lower severity categories, a release of radioactive materials is to be expected in only 50 % of accidents involving heavy goods vehicles. This percentage, obtained from the accident simulation program, is derived from the relative frequency with which the 9 severity categories (cf. Figure 8.3.8) are represented in road transport accidents in conjunction with the relative frequency of the 8 waste container groups of the transport volume. Unlike rail transport, only one shipping unit is affected by the accident in each case. Reference is made to the comments in the preceding Chapter 8.5.1 as regards the assumption made within the framework of transport risk analysis that on average every second accident involving an articulated lorry carrying a shipping unit considered in the accident statistics (cf. Appendix III) is associated with a release of radioactive materials. The anticipated accident frequencies with or without release within the 25 km radius zone for the 20 % road/80 % rail transport scenario are derived by totalizing the above accident frequencies and those for 80 % rail transport.

8.5.3 Braunschweig Marshalling Yard

The evaluation of the accident statistics for Braunschweig marshalling yard revealed 7.5 accident events per 1 million marshalled wagons. In addition, the probability with which a specific number of wagons is affected by an accident was calculated (cf. Table 8.3.3). In order to cover accidental occurrences and their frequencies in which more than one waste wagon is affected, as described in Chapter 8.3.2, the accident environment is assumed to comprise a group of wagons which is composed for onward transportation to Beddingen interchange station. As with railway goods traffic, it is assumed that the group of wagons consists on average of 30 wagons, including 1, 2, 3 ... 9 waste wagons with equal frequency. With the aid of Table 8.3.3 and combinatorial probabilities (cf. Appendix II), this model can be used to calculate that a statistical mean of 1.07 waste wagons is affected in the event of a marshalling accident involving at least one waste wagon. Consequently an accident probability per marshalled waste wagon of $8.0 \cdot 10^{-6}$ ($7.5 \cdot 10^{-6} \cdot 1.07$) can be expected.

During marshalling accidents (according to Table 8.3.3), accident loads corresponding to the three lowest severity categories occur. Concrete and cast iron containers (cf. waste container groups 6, 7 and 8 in Tables 8.2.1 and 8.2.2) are able to withstand the accidental load in some of the lower severity categories so that no release of radioactive material is assumed. Given the relative frequency with which different waste containers are represented in the total transport volume on the one hand, and the severity categories on the other, a release of radioactive substances can be anticipated in 38 % of marshalling accidents in which wagons with radioactive waste containers are affected. Reference is made to the comments at the end of Chapter 8.5.1 as regards the percentage determined within the framework of the transport risk analysis.

The frequency with which marshalling accidents at Braunschweig marshalling yard can be anticipated for the transport volume of radioactive waste in one year is calculated as follows:

- Given the assumption that all waste wagons transported by regular goods trains are routed through Braunschweig marshalling yard on their way to the KONRAD waste disposal site, 820 waste wagons per year will be marshalled there (with 100 % rail transport). Dedicated train loads carrying radioactive waste derived from reprocessing fuel elements from German nuclear reactors abroad will not pass through Braunschweig.

- The expected frequency of marshalling accidents in which one or more waste wagons are affected is given as follows:

$$820 \frac{\text{waste wagons}}{\text{a}} \cdot 8.0 \cdot 10^{-6} \frac{\text{Accidents}}{\text{Marsh.waste wagons}} = 6.6 \cdot 10^{-3} \frac{\text{Accidents}}{\text{a}}$$

- Since a release of radioactive material can be anticipated in 38 % of cases on average, the annual frequency of a marshalling accident with release is

$$6.6 \cdot 10^{-3} \text{a}^{-1} \cdot 0.38 = 2.5 \cdot 10^{-3} \text{a}^{-1}$$

Note again at this point, with reference to Chapters 8.2.1 and 8.2.2 and the comments at the end of Chapter 8.5.1, that the anticipated proportion of accident events with radioactive releases (here 38 %) is significantly influenced by a series of conservative assumptions. This relates in particular to the assumption made that waste packages are subjected to a mechanical load corresponding to an impact at 35 km/h on to an unyielding surface in the case of marshalling accidents, and that subsequent fires fully correspond to a constellation whereby the waste container is surrounded by fire on all sides and is exposed to these conditions for half an hour (load category 2) or even a full hour (load category 3).

The frequency of marshalling accidents in which radioactive materials are released, as anticipated by these very conservative assumptions is once in 400 years on average, assuming continuous operation of the KONRAD waste repository.

8.6 Results of Transport Risk Analysis

8.6.1 Calculation of Radiological Consequences

Substances released into the atmosphere as a result of an accident can be carried through the air and spread further as a consequence of air turbulence. As a result, contaminant concentrations at ground level can occur in the direction of wind while the contaminant cloud is passing over. Moreover, dry or (after rain) wet deposition processes can result in contamination of vegetation and other surfaces. People standing in

areas where increased atmospheric concentrations occur while the contaminant cloud is passing over in the atmosphere, can inhale the contaminant with respiratory air. Depending on the contaminant, further exposures can result from the contamination deposited on vegetation and other surfaces as time passes. The atmospheric dispersion conditions prevalent at the time of release, such as diffusion category, wind speed, precipitation intensity etc., considerably influence the airborne and deposited contaminant concentrations.

The potential accidental radiological consequences, such as contamination on vegetation or soil and radiation exposure of people, is calculated with the accident consequences computer code UFOMOD (Version NL) /EHR 88/ developed at the Nuclear Research Centre in Karlsruhe. This comprehensive and advanced program system has been specifically developed for the probabilistic analysis of accident consequences.

The following exposure pathways are taken into account:

- Cloudshine
- Groundshine
- Inhalation (intake of activity with respiratory air)
- Ingestion (intake of activity with food)
- Resuspension with subsequent inhalation (reentry of radionuclides into air subsequent deposition)

However, the cloudshine and resuspension exposure pathway are generally of minor importance, and so is the case with accidents involving waste packages.

The relative frequency of the atmospheric dispersion conditions in the region being investigated was included in the calculations. In this connection the meteorological data of the German Meteorological Service (DWD), Offenbach, collected at the Braunschweig-Völkenrode weather station situated north-west of the Braunschweig municipal area, were made available for the study.

The possible radiation exposure of people and contamination of vegetation and ground were calculated with the UFOMOD computer program for each release cate-

gory, for a distance up to 25 km from the release location. Since the spectrum of possible activity releases attributable to waste transport operations by rail, road and marshalling is covered by 10 release categories in each case, namely FK 1 to FK 10, calculations were made for a total of 30 release categories. The following assumptions were made in this connection:

- Ground-level release was assumed for the release categories FK 1 to FK 5, which are representative of transport accidents in which the waste packages are subjected to purely mechanical loads.
- As far as release categories FK 6 to FK 10 are concerned, which are representative of mechanical impact with subsequent fire, an effective release height of 50 m, was assumed to account for the buoyant nature of the plume of hot air.
- UFOMOD calculations were carried out separately and superimposed for each release category for particles < 10 µm and for the 10 - 70 µm particle size range. In this way the dispersion calculations allow for the fact that only particles < 10 µm are respirable and contribute to inhalation exposure. Similarly, the enhanced dry and (in the event of rain) wet deposition process of larger aerosol particles is taken into account for particles in the 10 - 70 µm size range.

For the purpose of accident risk analysis, fire incidents are treated as severe fires with particularly unfavourable effects on the waste containers with complete envelopment of the extremely large containers and adverse fire temperature (800°C) and duration (30 minutes, 60 minutes) combination. Such events correspond to a fire output of 20 MW and more, leading to substantial plume rise effect of the fire gases. The effective release height of 50 m, as assumed for the dispersion calculations, is conservatively set clearly lower than plume rise predictions of fire gases calculated with standard formulae, e.g. /VDI 87/.

The UFOMOD calculations provide the following results for each release category:

- Statistical distributions of airborne and deposited radionuclide concentrations are calculated as a result of the accident-related releases of activity for a very large number of receptor points, which are representative for various distances from the accident site and all wind directions. These statistical distributions result from frequency distributions of the prevalent atmospheric diffusion category, wind speed, wind direction and precipitation intensity.

- Starting from the statistical frequency distributions of the activity concentrations, distributions of the potential radiation exposure are calculated for each receptor point. The radiation exposure is expressed in terms of effective dose both for the individual exposure pathways and the total of all exposure pathways.

The results of the probabilistic risk analysis of waste transport accidents in the region of the waste disposal site are represented in the form of cumulative complementary frequency distributions (CCFD) for the following transportation scenarios:

- Waste transportation exclusively with goods trains (100 % rail)
- Waste transport partly with goods trains and partly with road vehicles (80 % rail/20 % road)
- Waste transport operations at Braunschweig marshalling yard

The CCFD's for each scenario are obtained by superimposing the results for the 10 release categories FK 1 to FK 10. In determining the consolidated cumulative complementary frequency distribution the expected frequency of occurrence of the individual release categories based on estimated accident frequencies of waste shipments in the 25 km zone has to be taken into account. These are summarized in the Table 8.6.1.

The expected frequencies of occurrence of the release categories are derived from the frequencies of transport accidents with release in the region of the waste repository explained in Chapter 8.5, multiplied by the conditional probabilities of the various release categories (cf. Figures 8.4.3, 8.4.4 and 8.4.5).

Expected frequencies are given in the complementary frequency distributions to levels as low as to 10^{-7} per year. The representation of even lower risk frequencies is felt to be inappropriate as other risks that are not even taken into account in the analysed accident statistics then contributes to the transport risk. For example, the frequency of a fast military aircraft crashing into a waste transport vehicle is for the comparatively small volume of waste transports of 3,400 shipping units approximately $3 \cdot 10^{-8}$ per year.

Table 8.6.1: Estimated Frequencies of Occurrence of the Release Categories for the 25 km Radius Zone of the KONRAD Waste Repository Following a Transport Accident

Release category	Goods train accidents 100 % rail transport [1/yr]	Road transport accidents 20 % road transport [1/yr]	Marshalling accidents 100 % rail transport [1/yr]
FK 1	$2.7 \cdot 10^{-4}$	$2.9 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
FK 2	$2.1 \cdot 10^{-4}$	$2.3 \cdot 10^{-3}$	$8.1 \cdot 10^{-4}$
FK 3	$5.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$
FK 4	$2.6 \cdot 10^{-6}$	$2.5 \cdot 10^{-5}$	$4.1 \cdot 10^{-6}$
FK 5	$3.4 \cdot 10^{-10}$	$1.2 \cdot 10^{-6}$	$1.1 \cdot 10^{-8}$
FK 6	$8.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$
FK 7	$6.6 \cdot 10^{-5}$	$8.9 \cdot 10^{-5}$	$2.0 \cdot 10^{-4}$
FK 8	$1.6 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$	$4.8 \cdot 10^{-5}$
FK 9	$8.1 \cdot 10^{-7}$	$9.1 \cdot 10^{-7}$	$2.3 \cdot 10^{-6}$
FK 10	$1.4 \cdot 10^{-9}$	$2.1 \cdot 10^{-9}$	$3.0 \cdot 10^{-9}$
Total	$7.0 \cdot 10^{-4}$	$6.0 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$

8.6.2 Reference Scenario: 100 % Rail Transport

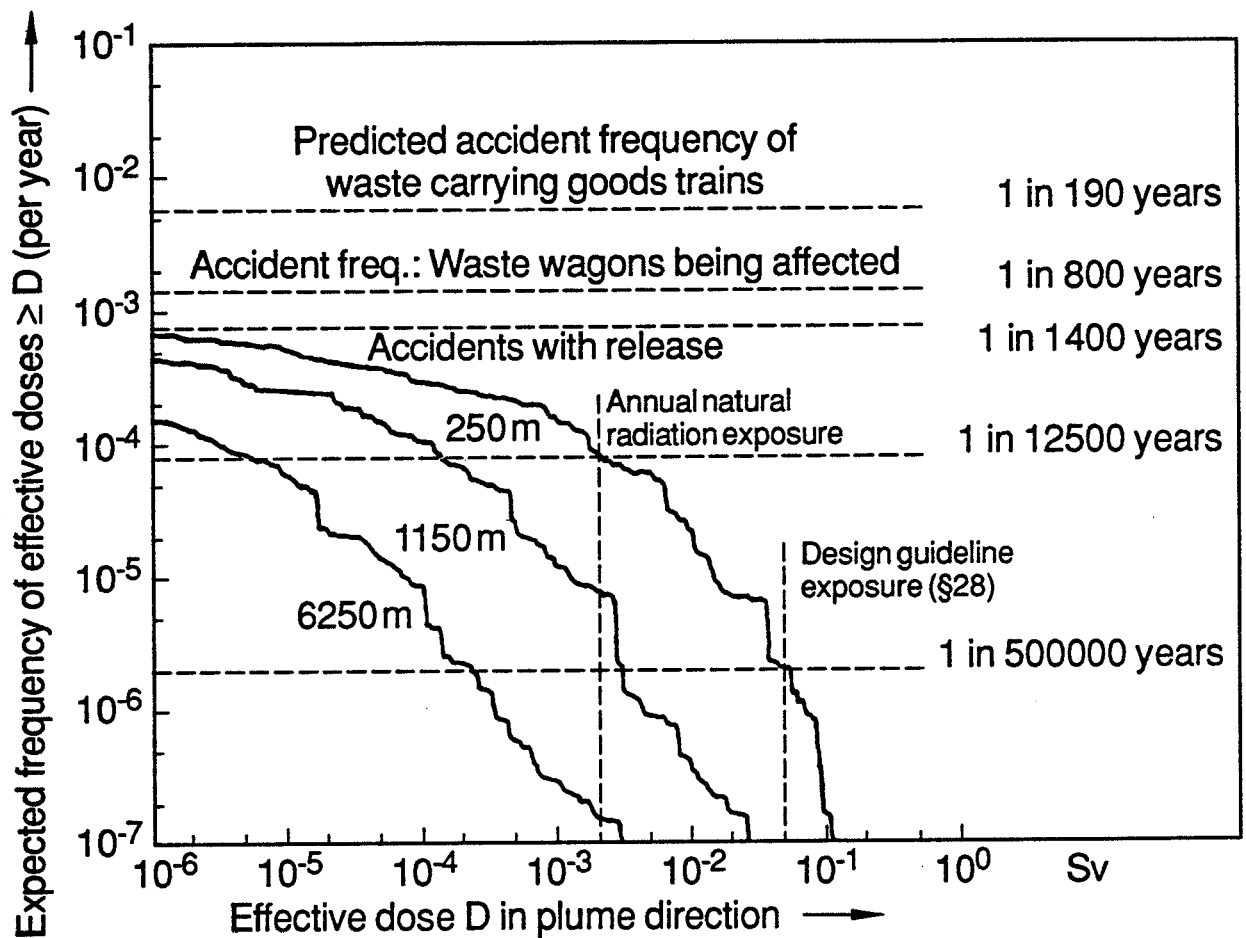
- Radiation exposure

The results as regards the risk of transport accidents for exclusive waste transportation by goods trains are summarized in Figure 8.6.1. The curves indicate the frequencies with which specific potential radiation doses can occur at various distances from the accident site following transport accidents.

The expected frequency per year with which the radiation exposure shown as effective doses on the horizontal axes can occur can be read off the vertical axis. Because of the wide ranges of values of anticipated frequencies of occurrence and potential doses, a logarithmic scale is used for both axes.

The following information is important for an understanding of the accident risk results summarized in Figure 8.6.1:

- The frequencies shown on the vertical axis refer to the entire region of the waste repository, that is to say to the zone within a radius of 25 km around the installation.
- The effective dose given on the horizontal axes indicates the potential dose to a person residing permanently in wind direction in close proximity to the accident site.
- In calculating potential radiation exposure levels as a result of releases of radioactive substances caused by accidents, it was assumed that a person is situated at certain distances from the accident site - e.g. 250 m, 1150 m, 6250 m - in the direction in which the contaminant cloud is dispersed by the prevailing wind.
- In this context it is assumed that the person considered remains outdoors during the passage of the airborne radioactive cloud (inhalation, cloudshine). In addition, that person continues to stay in that area for the following 70 years (groundshine) and derives his food from this location (ingestion).
- The curves given for the specified distances cover the potential resultant radiation exposure of persons for the entire spectrum of possible releases with transport accidents. They also give the frequency with which such radiological consequences can occur somewhere within the 25 km zone around the waste disposal site.



Basis: - 100% rail transport
 - No countermeasures

Figure 8.6.1: Frequency distribution of the effective lifetime dose from waste transport accidents in the region of the waste repository (25 km zone)

- No protective countermeasures are assumed in calculating the potential radiation doses. That is to say, in particular, that the removal of radioactive substances deposited on vegetation and other surfaces after an accident or other measures to reduce potential radiation exposure are not assumed.
- The frequency distributions refer specifically to potential radiation exposure in the direction where the peak concentration occurs. Other areas outside a sector of approximately 30° in the direction of atmospheric dispersion would not be affected.
- The shortest distance, for which the frequency distribution in Figure 8.6.1 is indicated, is 250 m. Calculations of potential radiation exposure assuming no countermeasures at all following an accident become increasingly unrealistic for shorter distances from an accident site. Furthermore, accidental sequences with fire that lead to substantially higher releases of particles in the respirable size range than results from purely mechanical impact on waste containers, are associated with rising of the hot effluents. In effect, this leads to maximum ground-level contaminant concentrations at distances of several hundred metres.

The following conclusions, among others, can be derived from the results summarized in Figure 8.6.1 as regards the accident risk from waste transportation by goods train:

- Referred to the waste transport volume for one year, the predicted frequency with which an accident involving the release of radioactive substances occurs in the region of the waste repository is $7 \cdot 10^{-4}$ per year.
- Since the quantity of radioactive substances released is frequently small, the potential radiation exposure obtained as a result is accordingly low. Thus, the calculated effective lifetime doses at a distance of 250 m from the accident site in the direction of atmospheric dispersion are in the range below 2 mSv in approximately 90 % of accidental events. This corresponds to the effective dose that a person receives on average from natural radiation sources in one year. This can be read off the curve for a distance of 250 m, whereby effective doses of 2 mSv or higher can occur with an anticipated frequency of $8 \cdot 10^{-5}$ per year referred to the waste transport volume for one year.
- At larger distances from the accident site, the predicted annual frequency of being exposed to potential doses subsequent accidental releases comparable to annual doses from natural sources is accordingly lower. Given the hypothetical continu-

ous operation of the waste repository, a transport accident without countermeasures that could lead to radiation exposure levels of the natural radiation exposure for one year at a distance of approximately 1,000 m could be anticipated in the vicinity of the waste disposal site with a frequency of occurrence of approximately $8 \cdot 10^{-6}$ per year, that is to say once in approx. 125,000 years.

- Accidents in which potential effective doses are in the 50 mSv range are accordingly less probable. 50 mSv corresponds to the design guideline exposure specified in § 28 Para. 3 of the Radiation Protection Ordinance and the annual dose limit for workers occupationally exposed to ionizing radiation.
- Potential doses of 50 mSv occurs at greater distances from the the accident site only with extremely low frequencies of occurrence on the order of 10^{-7} per year. Such radiation exposure could occur only in the immediate vicinity of accident locations with a very low predicted frequency of occurrence $2 \cdot 10^{-6}$ per annum) (250 m, in wind direction, no countermeasures).

The frequencies of occurrence shown in Figure 8.6.1 refer to the entire region of the waste repository (25 km radius). The individual risk from possible transport accidents involving radioactive waste to a person living close to a transport route lies in much lower ranges. The reasons for this include:

- An accident would have to occur near to his place of residence. Even if the route concerned is a stretch on which accidents are more likely to occur, the likelihood of an accident is clearly lower than for the region around the waste disposal site as a whole.
- In general, not all waste transports will be routed via the short stretch of interest here. Alternative transport routes are available.
- To be affected, the individual would have to be situated exactly in the direction of the dispersing plume, the probability of which is also lower.

The shortest distance from the accident site for which the frequency distribution of the effective dose is identified in Figure 8.6.1 is 250 m. As already discussed, there are two reasons for specifying this as the minimum distance:

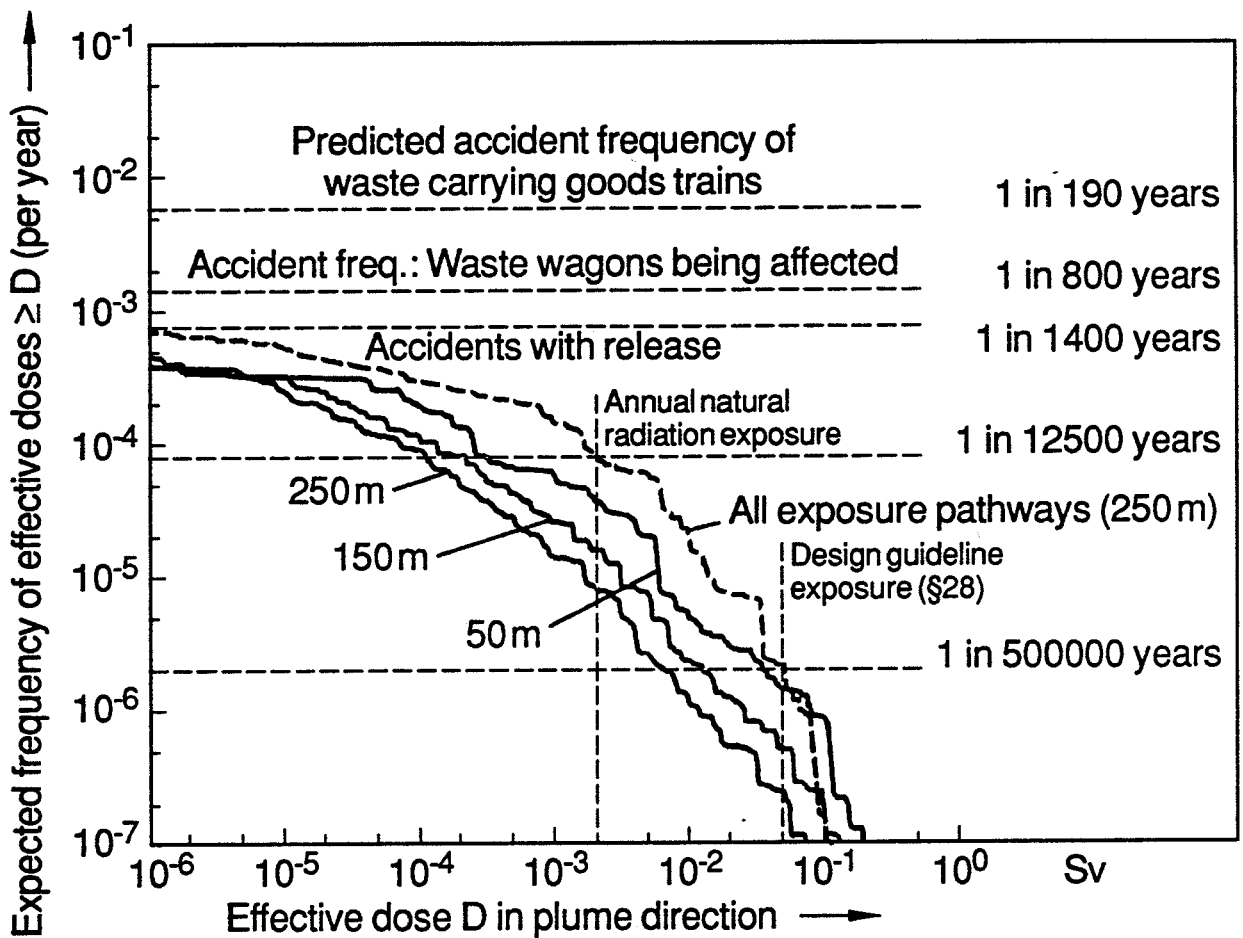
- The total dose from all exposure pathways is calculated, assuming no countermeasures are taken once the accident occurs. For shorter distances it is unrealistic to suppose that no countermeasures are taken at all to reduce the exposure

to long-term exposure pathways, such as groundshine, ingestion, and resuspension. In addition, the assumption that a person's food is entirely derived from distances of even less than 250 m from the accident site for a period of 70 years is highly unrealistic.

- Fire accidents lead to clearly higher releases of particles in the respirable size range than occur in the event of purely mechanical impact on waste containers. However, the released radioactive substances receive an upward thermal thrust from the hot fire gases so that the maximum ground-level contaminant concentrations will not occur through distances of several hundreds of metres from the accident site.

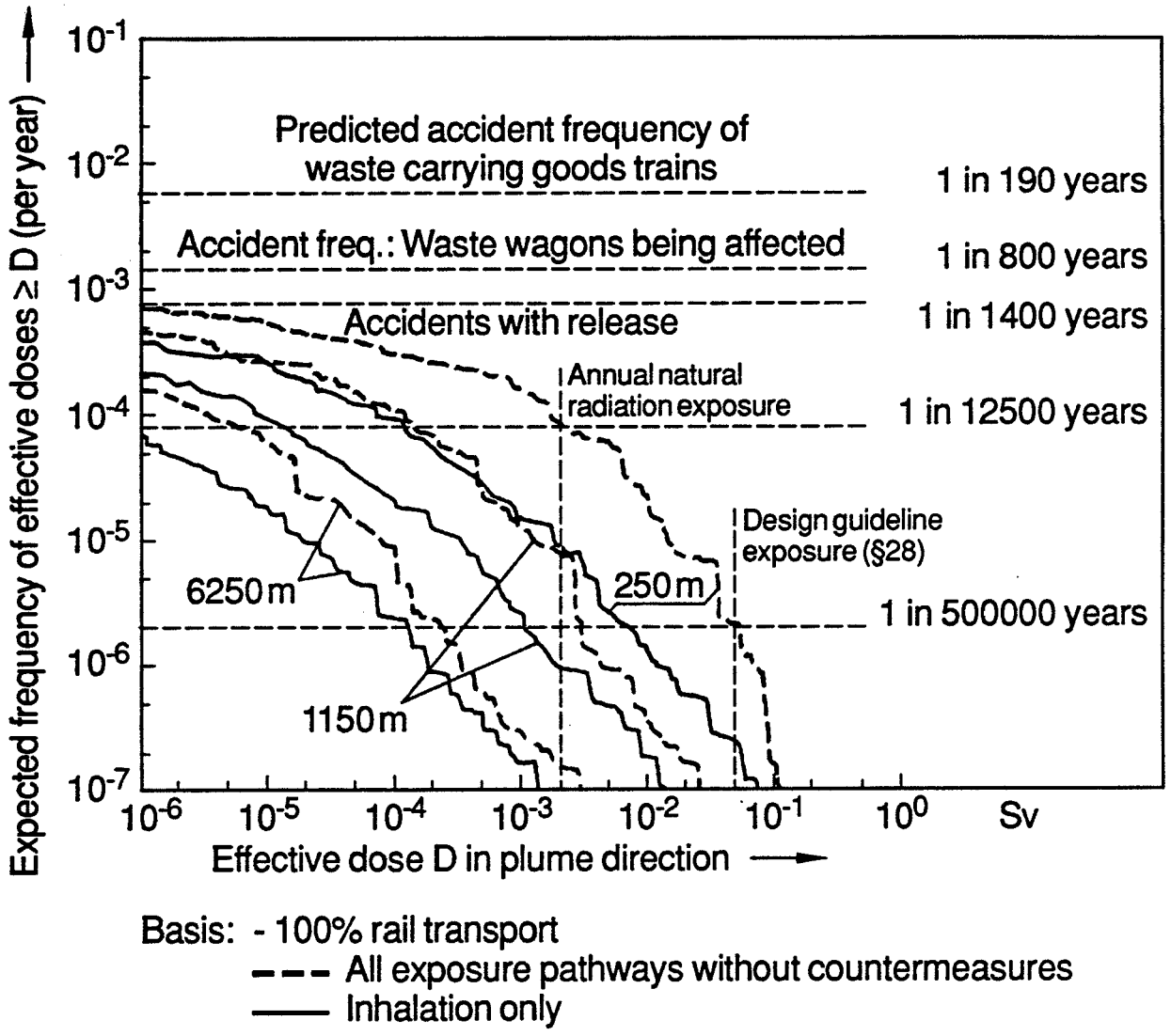
Nevertheless, for providing guidance, separate UFOMOD calculations were conducted for the shorter distances of 50 m and 150 m, as well as for 250 m from the accident site. The potential radiation exposure through inhalation was calculated. The corresponding cumulative complementary frequency distributions are illustrated in Figure 8.6.2. For comparative purposes, the frequency distribution of the effective dose cumulated for all exposure pathways for a distance of 250 m has also been taken over from Figure 8.6.1. The comparison reveals the contribution of the long-term exposure pathways, that is to say groundshine, ingestion and resuspension to the total dose. This also indicates to what extent measures taken after an accident can help to reduce radiation exposure. Figure 8.6.2 shows that the curve of the complementary frequency distribution of the effective total dose at 250 m almost entirely envelops the curves for the inhalation dose at closer distances to the accident site. This shows that potential effective doses are largely covered by the total dose identified for 250 m in the case of shorter distances from the accident site if the effects are limited to those derived from the inhalation pathway.

In order to assess the possible influence of measures to reduce radiation exposure taken after an accident also for larger distances in the direction of the dispersing plume, Figure 8.6.3 shows the curves for the total dose taken over from Figure 8.6.1 in relation to curves which state the contribution of the inhalation dose. The horizontal spacing of the pairs of curves at 250 m, 1150 m and 6250 m reveals the proportion of the total radiation exposure that results on average from the long-term exposure pathways, namely groundshine, ingestion, and resuspension, and can therefore be reduced by countermeasures such as decontamination or by suspending agricultural pro-



Basis: - 100% rail transport
 - - - All exposure pathways without countermeasures
 — Inhalation only

Figures 8.6.2: Frequency distribution of the effective lifetime dose from waste transport accidents in the region of the waste repository (25 km zone)



Figures 8.6.3: Frequency distribution of the effective lifetime dose from waste transport accidents in the region of the waste repository (25 km zone)

duction. Since the curves of the frequency distributions represent a large spectrum of accident sequences and atmospheric dispersion conditions, only general conclusions about the possible effect of countermeasures can be derived from a comparison of the total dose without countermeasures and the inhalation dose. Specific accidents can deviate from this in either direction. The relative contributions of the individual exposure paths to the total dose vary according to which radionuclides are released in the specific case, and depending on the ratio of deposited to airborne radioactivity. Deposition of radionuclides on vegetation and ground is more effective for wet conditions as a result of rain or by enhanced dry deposition processes of particles with larger aerodynamic diameters. The following information on the possible influence of measures taken after an accident can be derived from Figure 8.6.3:

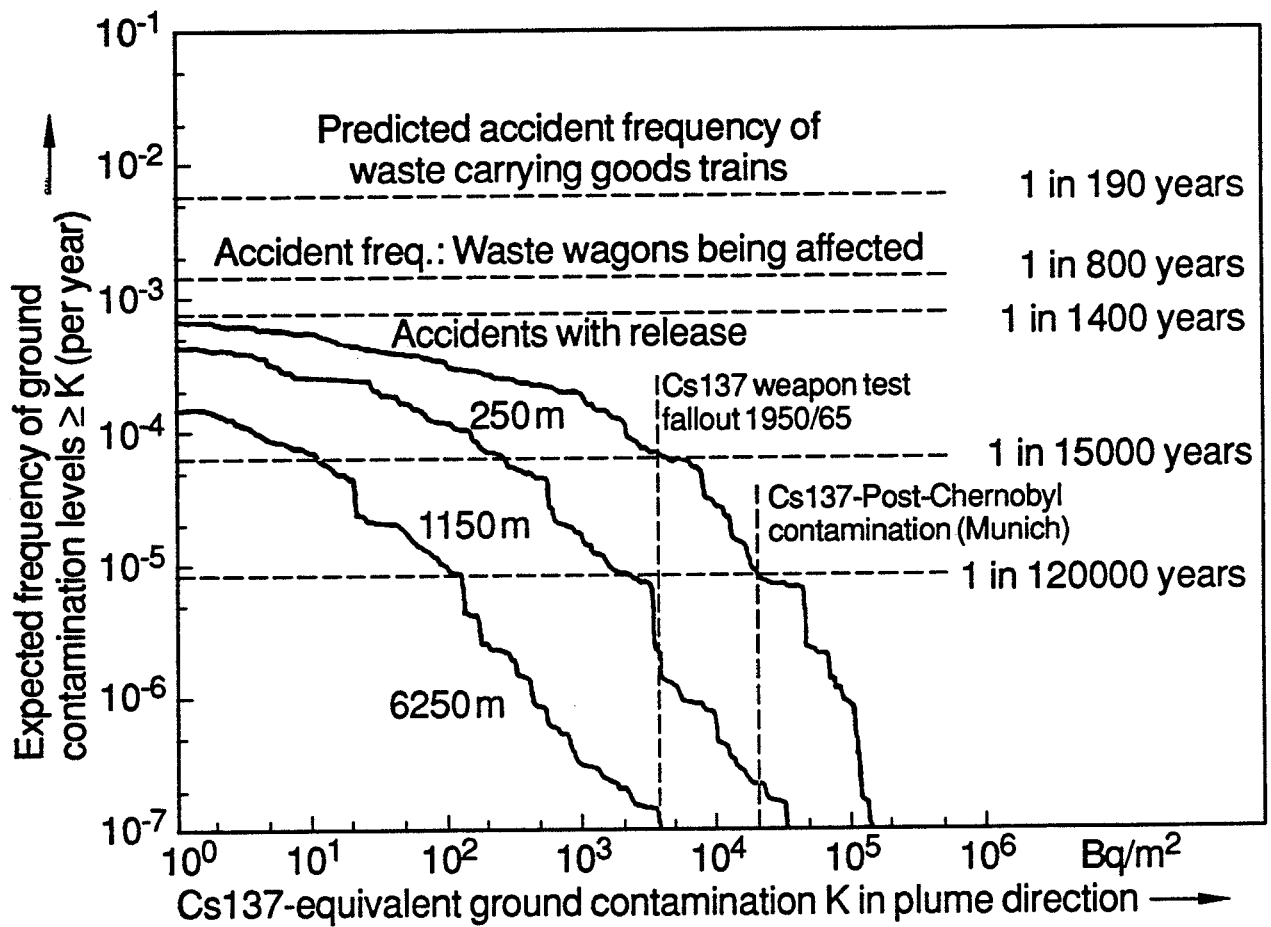
- The difference between the potential total dose and the inhalation dose is larger for shorter distances from the accident site, such as 250 m, than for larger distances, such as 1150 m and 6250 m. This can be primarily attributed to the fact that particles with larger aerodynamic diameters which do not remain airborne for long are deposited more profusely in the close vicinity of the accident site.
- Thus, at a distance of around 250 m from the accident site in the direction of the dispersing plume, measures which influence the long-term exposure pathways can typically achieve a dose reduction of a factor of approximately 10 and more in approximately 99 out of 100 accidents causing a release. At a distance range of approximately 1,000 m, the possible reduction of potential radiation exposure by means of countermeasures is measured by a factor of approximately 5. In this distance range, however, even without countermeasures, the predicted radiation exposure levels generally lie below the natural radiation exposure for one year and exceed this value only with anticipated frequencies of less than 10^{-5} per year.
- The less pronounced effect of countermeasures observed in all distance categories with very low anticipated frequencies of occurrence of 10^{-6} or 10^{-7} per year can be attributed, among other things, to the fact that accidents with fire add to the risk in this frequency range. In the case of releases with fire (cf. Table 8.2.1), the proportion of smaller particles in the respirable range is higher, so that the inhalation pathway makes a greater contribution to the total dose.
- The width (approx. 30° sector) and depth of the area potentially affected by transport accidents is limited. In only one out of 10 accidents with radioactive releases would it be possible for potential radiation exposure at a distance of 250 m and

without countermeasures to exceed the natural annual radiation exposure. At a distance of 1150 m this would be the case in only one accident out of 100 with releases and, at greater distances around 6,000 m, none at all would exceed this value.

- As discussed in greater detail below, the contribution of groundshine to the total dose is generally small and lies clearly below the amount of the ingestion pathway. The resultant potential radiation exposure over a period of 70 years is calculated for both exposure pathway, assuming permanent presence in the contaminated area and that all foodstuffs are obtained from agricultural products from that area. In the event of agricultural utilization of a more strongly contaminated area within the immediate vicinity of an accident site, countermeasures worthy of consideration would include administrative steps such as locally limited restrictions in land use.
- The range of predicted radiation doses is very well below dose values necessitating consideration of emergency protective measures. The countermeasures mentioned here are intended to highlight the possible influence of appropriate steps, and should be interpreted in the context of minimization principle required by the Precautionary Radiation Protection Act (StrVG).

- Contamination

Since accidental mechanical impact can also lead to the release of larger particles, aerosol particles with aerodynamic equivalent diameters of up to 70 μm have been included in the calculations of potential radiation exposure. These particles can be atmospherically dispersed, but are deposited much more quickly than particles in the respirable diameter range ($< 10 \mu\text{m}$). The calculations performed with the UFOMOD accident consequences program for the ten release categories FK 1 to FK 10 revealed that on average approximately 5 % of the potential radiation exposure can be attributed to groundshine. This value can be used to derive an appropriate cumulative complementary frequency distribution from Figure 8.6.1 for ground contamination caused by accidentally released radioactive substances. Both in fallout from nuclear weapon testing and the aftermath of the reactor accident in Chernobyl, Cs137 was the dominant radionuclide as regards ground contamination. For this reason, a Cs



Basis: - 100% rail transport
 - No countermeasures

Figures 8.6.4: Frequency distribution of the Cs137-equivalent ground contamination level from waste transport accidents in the region of the waste repository (25km zone)

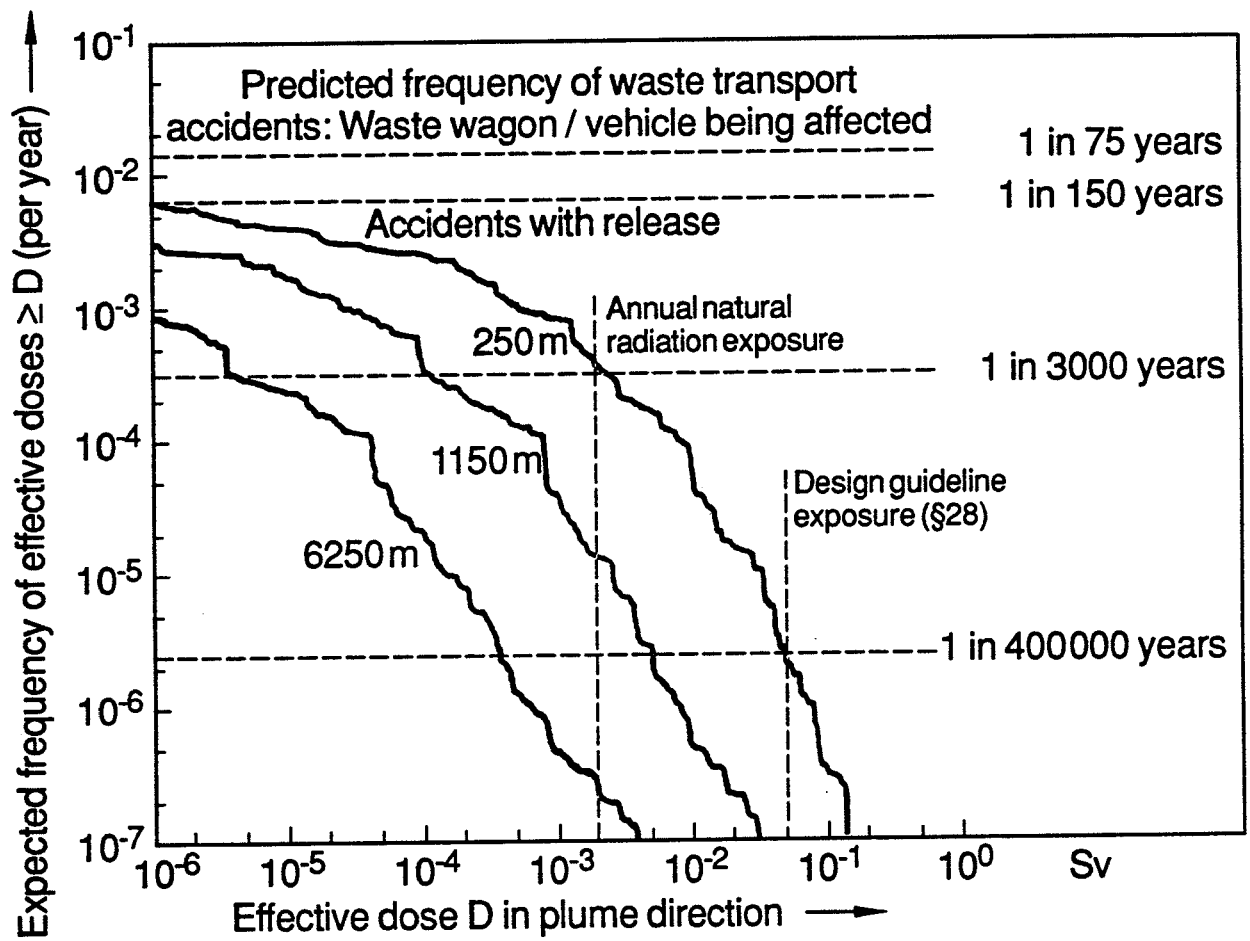
137-equivalent ground contamination level has been determined being equivalent to the groundshine dose from the all deposited radionuclides.

The result adapted from Figure 8.6.1 is the frequency distribution for Cs 137-equivalent ground contamination shown in Figure 8.6.4. The graph reveals the same curves. However, the expected frequency of ground contamination levels caused by transport accidents, expressed as Cs 137-equivalent, can now be read off. The following information can be derived from Figure 8.6.4, for instance:

- Accident-related releases in the region of the waste disposal site giving rise to a contamination level at a distance of 250 m from the accident site in wind direction that is equivalent to the Cs 137 nuclear weapon fallout in the Federal Republic of Germany occur with a frequency of less than $7 \cdot 10^{-4}$ per year.
- Given the hypothetical continuous operation of the waste repository, contamination on this scale could be anticipated at a distance of 1,000 m once in approx. 1 million years.
- Expressed as statistical mean, approximately one in 100 transport accidents lead to an Cs 137-equivalent contamination at a distance of 250 m from the accident site equivalent to that present in Munich as a result of the Chernobyl accident.

8.6.3 Reference Scenario: 80 % Rail Transport, 20 % Road Transport

The results as regards the risk of transport accidents when 80 % of shipping units are transported by goods train and 20 % by road vehicles are summarized in Figure 8.6.5. The curves are obtained by superimposing UFOMOD calculations for a total of 20 representative release categories, 10 each for goods train accidents and road transport accidents. The expected frequencies of occurrence for the individual release categories shown in Table 8.6.1 are taken into account in the cumulative complementary frequency distributions of Figure 8.6.5. The expected frequencies of occurrence for the release categories given in Table 8.6.1 for 100 % rail transportation, were corrected for the 80% transport fraction. The expected frequencies of occurrence of the individual release categories for road transport accidents are higher than with rail transport accidents. This reflects the higher accident frequency per truck-Kilometer travelled than per railway wagon-Kilometer for goods trains. This is also indicated by



Basis: - 80% rail / 20% road transportation
 - No countermeasures

Figures 8.6.5: Frequency distribution of the effective lifetime dose from waste transport accidents in the region of the waste repository (25km zone)

the expected frequencies of releases of $7.0 \cdot 10^{-4}$ per year for the 100% rail transport scenario and $6.0 \cdot 10^{-3}$ per year for the 20 % road transport scenario stated in Table 8.6.1 for transport accidents.

The following information can be obtained from Figure 8.6.5:

- In comparison with the cumulative complementary frequency distributions for the 100 % rail scenario in Figure 8.6.1, the expected frequencies for accidental releases and for effective lifetime doses comparable to the natural radiation exposure in one year or being in the dose range of 50 mSv, are higher.
- With a frequency of occurrence of approx. $3 \cdot 10^{-4}$ per year, that is to say assuming continuous operation of the waste disposal site, a transport accident in the region of the waste disposal site that could lead to radiation exposures equivalent to the natural radiation exposure in one year at a distance of 250 m could be anticipated every 3,000 years on average, assuming no countermeasures are taken. A comparison shows that, for 100 % rail transport, the transport risk analysis results in a lower frequency of occurrence, according to which such effects occur on average only every 12,500 years.
- For the operational lifetime of the waste repository of approximately 40 years the probability of a transport accident resulting in potential effective doses of 50 mSv at a distance of 250 m (without countermeasures) occurring in the region of the waste disposal site is 1 in 10,000. The dose of 50 mSv corresponds to the design guideline exposure stipulated in § 28 Para. 3 of the Radiation Protection Ordinance, and to the annual dose limit for workers occupationally exposed to ionizing radiation.
- The decrease in the calculated radiation exposure levels at a distance from the accident site of approximately 1,200 m amounts to a factor of approximately 10, with a further factor of 10 being valid at approximately 6,200 m.

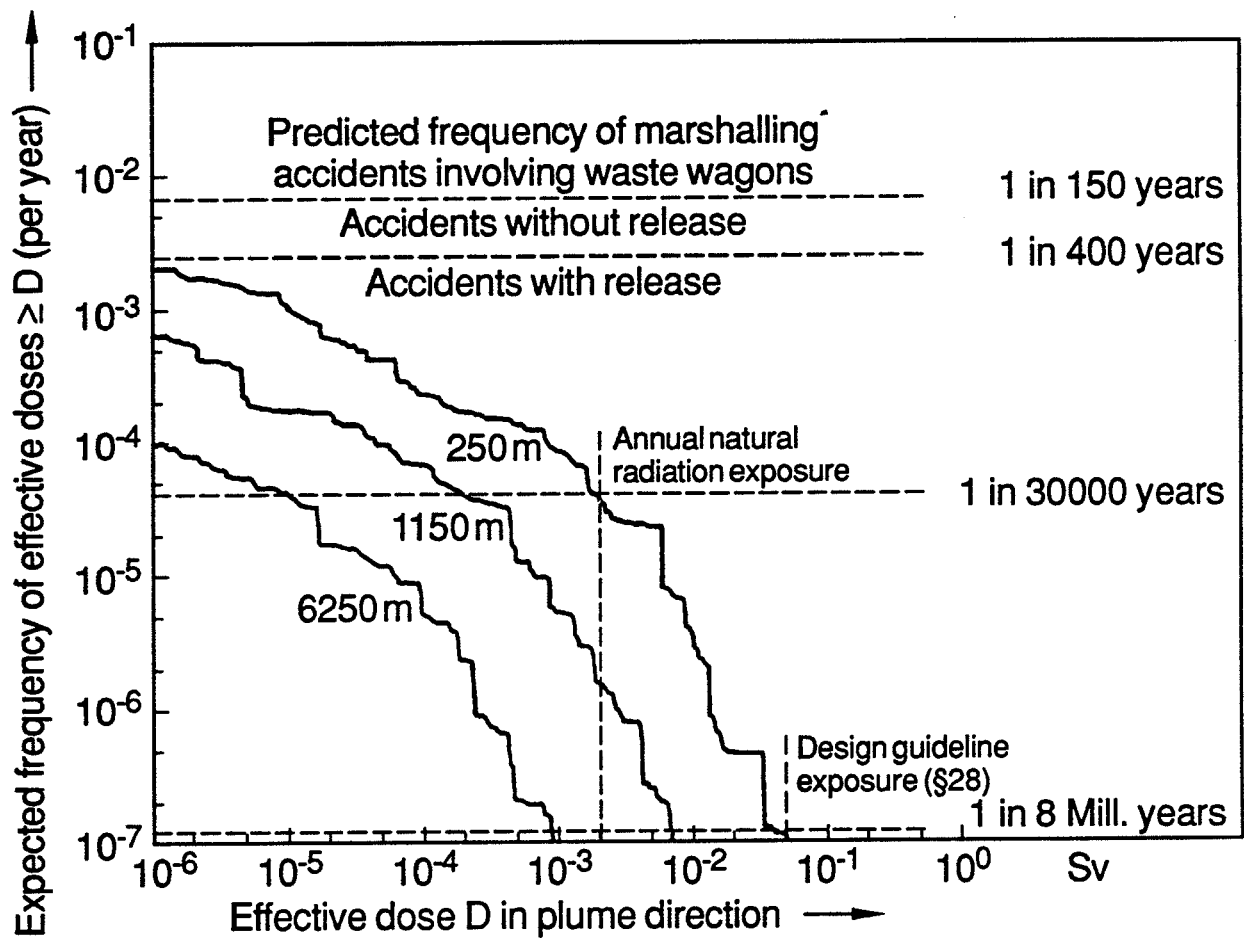
8.6.4 Braunschweig Marshalling Yard

- Radiation Exposure

The results as regards the risk of marshalling accidents at the Braunschweig marshalling yard are summarized in Figure 8.6.6. The cumulative complementary frequency distributions are based on the assumption that all waste shipments from waste consignors in the Federal Republic of Germany (not including the 5 new federal states) are effected by regular goods trains and are routed via Braunschweig marshalling yard. Transports derived from the return of reprocessing waste from abroad are effected in dedicated trains and are routed directly to Beddingen interchange station. The expected frequencies of effective lifetime doses with marshalling accidents shown in Figure 8.6.6 refer to the 100 % rail transport scenario. The frequencies are reduced by around 40 % for the 80 % rail/20 % transport scenario. They would fall even further if dedicated trains were also used in some cases for waste consignors with high volumes of waste.

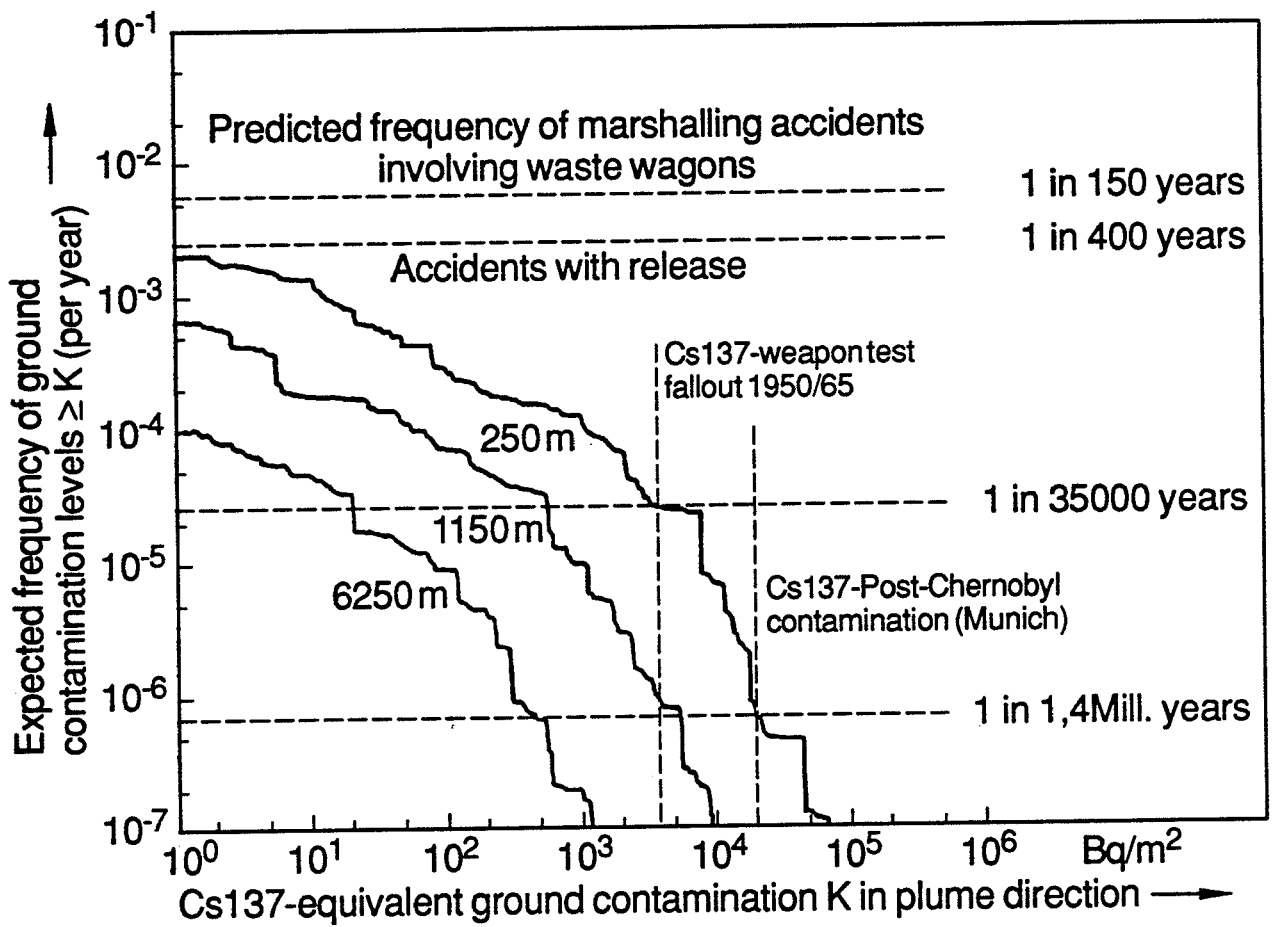
The following information can be obtained from the curves shown in Figure 8.6.6:

- During the 40-year operating period of the waste repository, a marshalling accident resulting in radioactive releases can be anticipated with a probability of 1 in 10.
- The frequency of releases caused by accidents leading to potential radiation exposure levels that exceed the average annual natural radiation exposure (2 mSv) at a distance of 250 m (assuming no countermeasures) is limited to approx. 1.3 % of this kind of accidents.
- Given the hypothetical continuous operation of the waste repository, a severe marshalling accident in which an effective lifetime dose according to the design guideline exposure of § 28 Para. 3 of the Radiation Protection Ordinance (50 mSv) would occur at a distance of 250 m without countermeasures could on average be anticipated once every 8 million years.
- The potential radiation exposure levels falls off substantially as the distance from the accident location increases: by a factor of approximately 10 at a distance of 1 km (1150 m), and by a factor of 100 at a distance of 6 km (6250 m).



Basis: - Regular goods train transport
 - No countermeasures

Figure 8.6.6: Frequency distribution of the effective lifetime dose from accidents at Braunschweig marshalling yard



Basis: - Regular goods train transport
 - No countermeasures

Figures 8.6.7: Frequency distribution of the Cs137-equivalent ground contamination level from accidents at Braunschweig marshalling yard

- **Ground Contamination**

The frequency distribution for the Cs 137-equivalent ground contamination shown in Figure 8.6.7 has been derived from Figure 8.6.6. In converting dose into Cs 137-equivalent quantities, the procedure described in Chapter 8.6.2 was used. If a marshalling accident involving a release occurs at all, then it is unlikely that it would cause ground contamination equivalent to dose levels resulting from Cs 137 nuclear weapon fallout or from the Cs 137 contamination arising in Munich following the Chernobyl reactor accident, at distances of 250 m and more from the accident site. Cs 137-equivalent ground contamination such as that experienced in Munich after Chernobyl would occur at a distance of 250 m in less than one in 1,000 marshalling accidents. A comparison of the soil contamination at 250 m in wind direction with the contamination at 1150 m reveals a decrease of approximately one order of magnitude.

8.7 Evaluation of the Transport Accident Risk

The results showing the transport accident risk are provided in the form of cumulative complementary frequency distributions indicating the relationship between the potential radiation exposure and the expected frequency of occurrence. This type of risk analysis covers both comparatively minor transport accidents, where radioactive releases are low, as well as severe accidental sequences with comparatively high releases and associated potential radiation exposure. Providing simultaneously information on the frequency and the extent of the potential radiological consequences in the region of the waste disposal site enables to draw conclusions about the risk of waste transport accidents. Although frequently not considered explicitly in everyday life, probabilities of occurrence are often taken into account implicitly. It is hardly conceivable, for instance, that passenger aircrafts would have gained acceptance as a common means of transport had their accident risk been e. g. 1,000 times greater. Manned expeditions into space were preceded by detailed risk analyses incorporating probabilistic methods for determining the chances of a successful return from such missions.

Expected frequencies to levels down to 10^{-7} per year are identified in Figures 8.6.1 to 8.6.7. Referred to the waste transport volume for one year, this figure signifies that there is a probability of 1 in 10 million per year of an accident with specified radiological consequences occurring in the region of the waste repository. Low probabilities of occurrence on this scale can be grasped more readily by comparing this figure to

other rare events. This approach also allows a justification of why events with even lower probabilities of occurrence but higher consequences were not considered in the study: the probability of an air crash of a fast-flying military aircraft as observed in the past in the Federal Republic of Germany (prior to the accession of the former GDR) is approximately $10^{-10} \text{m}^{-2} \cdot \text{a}^{-1}$. This permits the determination of the expected frequency with which such an air crash would affect a wagon or a truck carrying radioactive waste. Taking the travel and stopping times of waste transports inside the 25 km radius zone of the waste disposal site into account, the frequency of such events is calculated to be approximately $2 \cdot 10^{-8}$ per year. In other words, compared to an expected frequency of 10^{-7} per year, an air crash of a fast-flying aircraft on a waste container is less likely only by approximately a factor of 5. The representation of events with even lower probabilities of occurrence in the frequency distributions shown in Figures 8.6.1 to 8.6.7 would therefore make little sense since at this probability level other accidental occurrences which are not included in the analysed data bases of rail and road accidents, such as aircraft crashes, may contribute to the transport risk. In addition, an air crash of a fast-flying military aircraft into a normal goods wagon - and even more on a comparatively much rarer wagon containing radioactive waste packages - in the region of the waste disposal site must be qualified without doubt as an extremely rare occurrence.

The expected frequencies of specific accidental consequences, such as exposure to radiation or contamination, identified in Figure 8.6.1 to 8.6.7 refer to the entire region within a 25 km radius of the planned KONRAD waste disposal site. They therefore draw a conclusion as to the accident risk in this entire area. The risk to specific individuals of this region of being affected by an accident involving waste transports is very much smaller. This risk will be estimated here in order to provide an approximate orientation, with the aim to roughly estimate the order of magnitude of this risk: For the 100 % rail transportation scenario, Figure 8.6.1 indicates that transport accidents which result in radiation exposure levels at 250 m corresponding to or exceeding the average natural radiation exposure from one year can be anticipated with a frequency of approx. 10^{-4} per year. A similar value is found for radiation exposures at distances below 250 m by consulting Figure 8.6.2; its results assume that, within a distance of 250 m, countermeasures are taken concerning the long-term exposure pathways such as ground shine and ingestion (inhalation path only).

Transport accidents can occur anywhere on the transport routes. For the purpose of simplification, if a 50 km section of railway line on which the waste transports travel in the region of the waste disposal site is considered (although the route network used for waste transportation is longer) together with a corridor of a depth of 250 m on either side along the transport route, approx. 6,000 human beings can be assumed to live in this immediate area assuming an average population density of 250 inhabitants per square kilometre. If an accident were to occur anywhere on this 50 km section of the track, up to 250 m in down wind direction an area would be affected forming a sector with an aperture angle of approx. 30°. This would result in an area of approx. 0.02 square km. According to the average population density, 5 people live in an area of this size, again supposing an average population density of 250 inhabitants per square kilometre. The individual risk for individuals living immediately adjacent to the route of receiving additional radiation exposure as a result of a transport accident equivalent to the range of natural radiation exposure received in one year is therefore approx. $8 \cdot 10^{-8}$ per year. This figure is intended to permit only an approximate orientation as to the scale on which the individual risk under consideration lies. To explain the significance more clearly, if this figure is compared with the annual individual risk of being seriously injured in a road traffic accident, it can be seen that this is on quite a different scale: According to the 1990 Statistical Yearbook of Lower Saxony, 14130 people in a population of 7.1 million were seriously injured in road accidents in 1988. Thus, the individual risk of being seriously injured in a road accident is $2 \cdot 10^{-3}$ per year. Without wishing to compare any radiation exposure on the scale of the annual natural radiation exposure with a serious injury from an accident, the above numerical comparison immediately reveals that the additional individual risk attributable to possible waste transport accidents is on a much lower scale than other risks such as those arising from road traffic, and is therefore very much less significant by comparison.

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