Methods and Results of a Probabilistic Risk Assessment for Radioactive Waste Transports

F. Lange, D. Gründler, G. Schwarz

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, D-5000 Cologne, Germany

1 Introduction

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 near Salzgitter in Germany. The expected annual transport volume is about 3400 shipping units. One main objective of the study was the assessment of radiological risks from transport accidents in the region of the final repository. Two shipping scenarios, which can be considered to bound the real conditions, were analyzed:

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

To a large extent probabilistic safety analysis techniques have been applied in order to take account of the variational range of quantities and parameters which determine potential radiological consequences of transport accidents and the expected frequencies of their occurrence. Influencing quantities and parameters are:

- 217 waste categories representing different type of waste, packaging and radionuclide inventory,
- 9 severity categories to classify the spectrum of accidental impacts,
- 8 waste package groups representing the release behavior of containers and waste products,
- Different loading configurations of vehicles and varying numbers of waste wagons within a train,
- Expected frequencies of accident severity categories and, with respect to rail transports, of the number of waste wagons affected in an accident,
- Variability of atmospheric dispersion conditions and consequently of potential radiation exposures from accidental releases.

Some background information will be given concerning those quantities and parameters which influence the expected frequencies of activity releases (source terms) from transport accidents. Probabilistic sampling techniques are applied to generate first a large number of potential source terms to represent possible releases from transport accidents. How these can then be reduced to a limited number of source terms, so-called release categories, will be described in some detail. These release categories along with their expected annual frequencies of occurrence should be representative with respect to the radionuclide composition and the released activities of individual radionuclides for calculating potential radiological consequences and their expected frequencies. Finally some results of the safety analysis will be presented and discussed.

2 Data and Data Bases

2.1 Waste Categories

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, which are basically the IAEA transport regulations and the acceptance criteria of the final waste repository 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 German Federal Office for Radiation Protection (BfS) was of fundamental importance to the safety analysis. Completed in the summer of 1990, the 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). The spectrum of radioactive waste suitable for disposal in the KONRAD waste repository was subdivided into 217 reference waste types which include the following information:

- origin/originator
- type of waste
- conditioning-/immobilization type
- type of packaging
- radionuclide inventory
- local dose rate of the package
- mean annual number of packages

There are three main types of standardized transport containers accepted for disposal: Cylindrical concrete containers, cylindrical cast iron containers and cubical containers (sheet steel, cast iron or concrete).

2.2 Severity Categories

The mechanical and/or thermal impact on the waste containers caused by the accident together with the properties of the waste containers and the waste product they contain (e.g. cement/concrete, bitumen, compacted waste etc.), determine the extent to which radioactive materials are released into the environment. 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 (SC) were defined with the characteristics shown in Table 3.1 (cf Fett and Lange 1992, this conference).

3 Waste Package Groups and Release Fractions

Releases of activity from accidental impacts depend on the properties of the transport container and the waste product which it contains. For this reason, the range of waste containers in use is divided into waste package groups (WPG) with the aim of categorizing waste containers with similar release characteristics in a single group. Eight waste package groups are distinguished:

WPG 1 Bituminized waste in sheet steel cubical containers
WPG 2 Non-immobilized and non-compactable metallic and non-metallic waste in sheet steel cubical containers
WPG 3 Metallic waste in sheet steel cubical containers
WPG 4 Compacted waste in sheet steel cubical containers
WPG 5 Waste immobilized in cement in sheet steel cubical containers
WPG 6 Bituminized waste in concrete containers
WPG 7 Waste immobilized in cement in concrete containers
WPG 8 Waste in cast iron containers

Airborne fractional releases from waste packages suffering a transport accident were determined for the 8 waste container classes and 9 severity categories defined above for particles in the following size range intervals of aerodynamic equivalent diameter (AED): 0 - 10 μm, 10 - 20 μm, 20 - 50 μm and 50 - 70 μm. The fractional releases for particles smaller than 10 μm are given in (Gründler et al 1991).

3.1 Accident Frequencies

Detailed analyses have been performed to determine expected accident frequencies per vehicle-km for heavy trucks (articulated lorries), per goods-train-km and per rail car-km and to assess the relative frequencies of the 9 severity categories in each case. Details of the analysis of German rail accident statistics of goods-trains for a 10 year period for this purpose are given in (Fett and Lange 1992).

Impact Velocity		Relative Frequency					
		without thermal impact		thermal impact 30 min., 800°C		thermal impact 60 min., 800°C	
0 to 35	km/h	0.5	(SC 1)	1.1E-2	(SC 2)	8.4E-4	(SC 3)
36 to 80	km/h	0.43	(SC 4)	9.5E-3	(SC 5)	7.6E-4	(SC 6)
above 80	km/h	4.8E-2	(SC 7)	1.1E-3	(SC 8)	8.4E-5	(SC 9)

Table 3.1: Relative frequency of severity categories (SC) for truck accidents

The overall accident rate for articulated lorries on federal motorways was determined to be $3.5 \cdot 10^{-7}$ km^{-1}. As accident rates of freight trains $5 \cdot 10^{-7}$ per train-km and of $2.5 \cdot 10^{-8}$ per rail-car-km was established. Since the waste containers can have a weight up to 20 tons transports by truck are assumed to use articulated lorries. The location of the waste repository allows the waste to be shipped almost exclusively on federal motorways. The relative frequencies of the 9 severity categories for road transport accident which were determined from truck accident statistics are given in Table 3.1.

4 Probabilistic Source Term Determination

4.1 Source Term Generation

A computer code was developed to simulate a wide spectrum of waste transport and accident configurations using Monte Carlo sampling techniques. In a first step a large number (e.g. 10000) of source terms are generated to represent possible releases of radionuclides from transport accidents. Accident events in which the integrity of waste packages is retained and consequently no releases occur are also recorded. Source terms are determined separately for road and rail transports.

One possible approach using Monte Carlo sampling would be:

- Choose the accident severity category taking into account the relative frequencies of different severity categories (cf Table 2.1).
- Choose the loading of the vehicle (truck) or of wagons of a freight train taking into account the 217 reference waste types and their respective share of the total transport volume.
- Determine the source term (activity release) for the chosen configuration of accident severity and affected waste containers.

This method is described in (Gründler et al. 1991). It has the disadvantage that severity categories with a low relative frequency given an accident (e.g. severity categories representing large mechanical impact followed by a fire) are rarely chosen by this approach. Whereas the aim of the probabilistic risk assessment is to also identify and be representative for very rare accident configurations of severity category and effected waste containers.

Another possible method which avoids this problem is to choose each severity category an equal number of times irrespective of its relative frequency but to record for each generated source term the probability of the accident configuration conditional that an accident has happened. For truck accidents this conditional probability coincides with the relative frequency of the respective severity category. In the case of train accidents the conditional probability of the accident configuration is more complicated since the number of rail cars affected has to be taken into account (Fett and Lange 1992) The conditional probability of the accident configuration recorded with each source term can then be used at a later stage of the probabilistic safety analysis in a proper way, as described below.

4.2 Relative Radiological Hazard Index

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

4.3 Source Term Groups and Release Categories

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

- The severity category (k = 1,2,3....9)
- The conditional probability of the accident configuration (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 potential radiological consequences

To facilitate the analysis of environmental consequences, the large number of source terms must first be appropriately grouped into a limited number of source term groups. In a next step for each source term group a representative source term is determined designated as release category. The procedure to determine representative source term groups is described taking reference to Figs. 3.1 and 3.2. Source terms generated by the accident simulation program are characterized by the associated radiological hazard index and the conditional probability of the accident configuration. Simulated source terms, taking road accidents as an example, are presented in Fig. 3.1 in a coordinate system with the radiological hazard index as x-axis and the conditional probability of the accident configuration as the y-axis, both in logarithmic scale.

Each point represents one source term. Source terms of the same severity category are positioned on a horizontal line which would intersect the vertical axis at the relative frequency of the severity category as given in Table 2.2. The wide spread of typically more than four orders of magnitude in the radiological hazard index of source terms belonging to the same severity category is due to the large differences in radionuclide inventory and release behavior (waste package groups) among the 217 reference waste categories.

In a next step the source terms are first arranged in ascending order according to the radiological hazard index. This is done separately for purely mechanical and combined mechanical/thermal severity categories. The reason for this is that in the calculation of radiological consequences an effective release height of 2 m is assumed for accidents with mechanical impacts only and of 50 m in the case of mechanical impact followed by a fire. After grouping the source terms according to increasing radiological hazard index and normalization to the summed probability of all source terms the cumulative complementary fre-

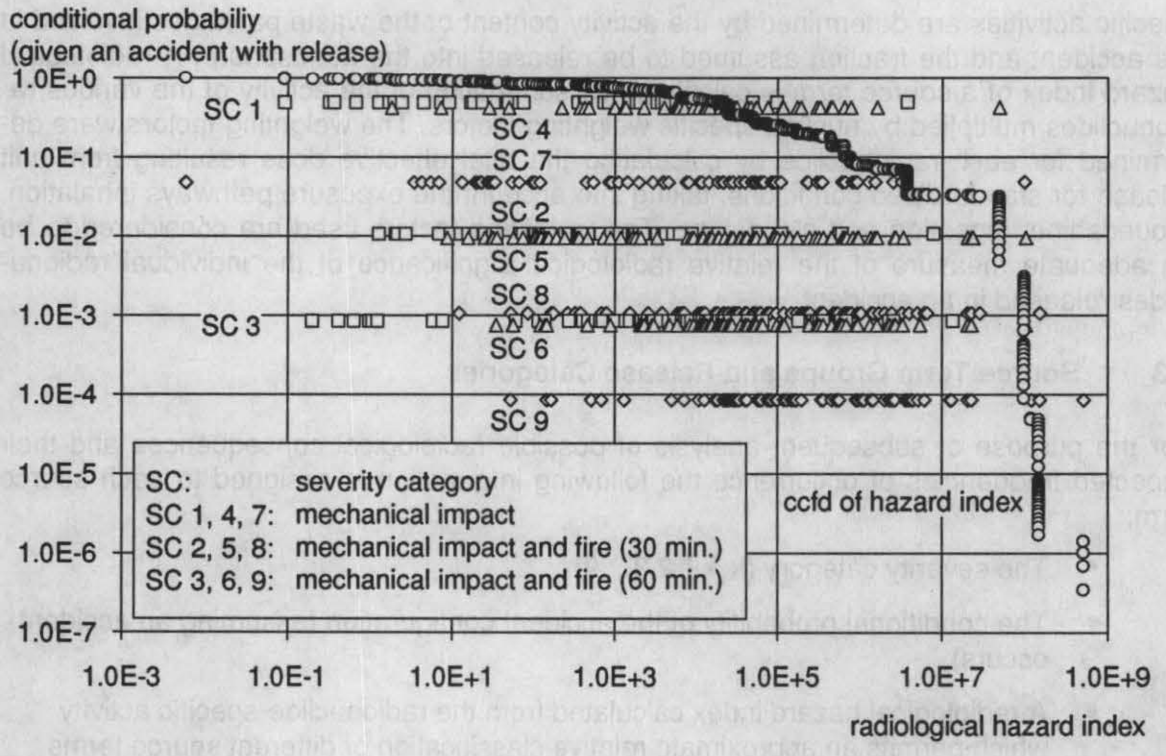

Fig. 3.1: Monte Carlo generated source terms and associated cumulative complementary frequency distribution of radiological hazard index (truck accidents)

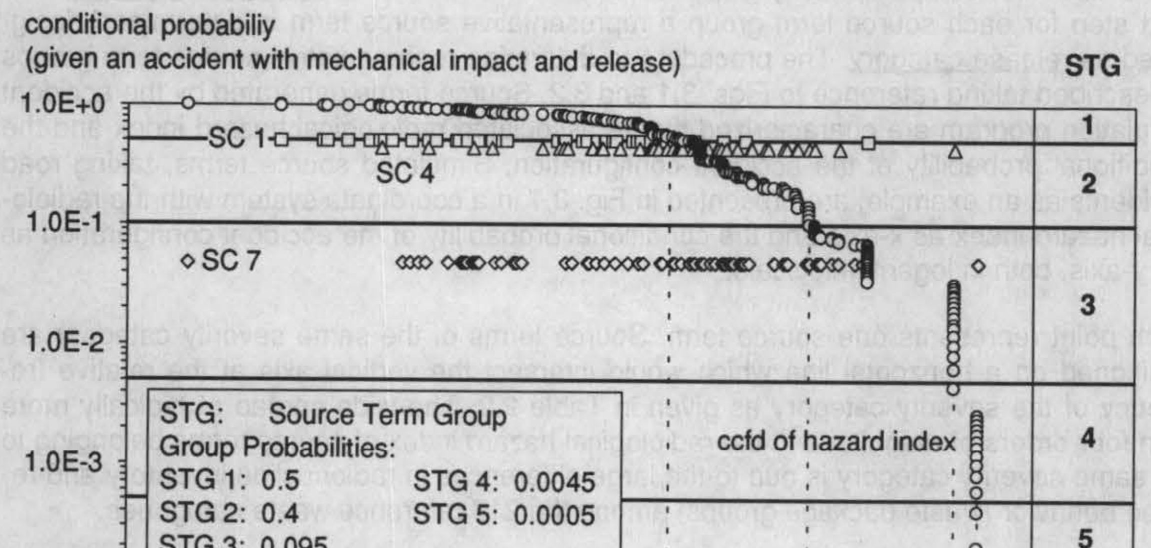

Fig 3.2: Generation of source term groups on the basis of conditional probabilities and radiological hazard index (truck accidents with mechanical impact)

quency distribution (ccfd) of the radiological hazard index as shown in Fig. 3.1 for all 9 release categories and in Fig. 3.2 for release categories with mechanical impact only can be constructed.

Source term groups are then formed by combining source terms with approximately equal hazard indices. This is done on the basis of the cumulative probability in a way that the range of radiological hazard indices of source terms having high hazard indices does not differ substantially. This procedure is intended to assure representativeness particularly for the source terms resulting in higher radiological consequences. As can be seen in Fig. 3.2 the determination of the 5 source term groups is according to the probabilities given in the following table:

source term group	fraction of cumulative probability	cumulative probability
1	0,5000	0,5000
2	0,4000	0,9000
3	0,0950	0,9950
4	0,0045	0,9995
5	0,0005	1,0000

Table 4.1: Cumulative probability for source term determination

In a next step for each source term group a representative source term, called release category, is derived. By taking the conditional probabilities of occurrence of individual source terms as the relative weight, a weighted average of the activities of individual radionuclides of the source terms within a group is calculated and in this way the radionuclide composition and activities of the release category determined. In summary, ten such release categories each have been generated by the simulation program for accidents during transportation by 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 (defined as circumference with 25 km radius) of the final repository.

5 Results

Potential radiological consequences, expressed as effective dose from the exposure pathways inhalation, cloudshine, groundshine (70 a), ingestion (70 a) and resuspension (70a), have been calculated using the UFOMOD computer code. The calculations assume no counter-measures and take into account the relative frequency of different atmospheric dispersion conditions in the region of the final waste repository. Results of the probabilistic risk analysis of transport accident in the region of the final repository are expressed as cumulative complementary frequency distributions (ccfd). These are the result of the superposition of the release categories representing potential releases from transport accidents, taking into account their relative frequencies. The cumulative complementary frequency distribution curves show the expected frequencies of radiological consequences from transport accidents. The expected frequencies refer to the region (25 km zone) of the final waste repository. Fig. 5.1 shows as an example the expected frequencies of effective doses for the 20% road transport scenario. As can be seen accidents of trucks carrying radioactive waste within the 25 km zone around the repository would be expected on average every 80 years. As a result of the accident analysis every second truck accident would lead to a release of radioactivity. But it has to be stressed that this rather high fraction is the result of a cumulation of conservative assumptions within the risk analysis. Nevertheless, in many accidents with airborne release of radioactive material potential radiological consequences would be quite small. The chances that a truck accident in the region of the repository would lead without counter-measures to an effective dose in 250 m down-wind distance from the location of the accident equivalent to or exceeding the natural radiation exposure of one year are about 1 in 100 for an operating period of 40 years. Effective lifetime doses of 50 mSv in 250 m down-wind direction from the location of a truck accident would be expected with a chance of 1 in 25000 during an operating period of the repository of 40 years. As can be seen from Fig. 5.1 potential radiation exposures decrease rapidly with distance from the location of the accident, starting from 250 m up to about 1200 m by a factor of 10 and a further factor of 10 at a distance of about 6200 m.

It can be concluded from the results of the risk analysis that the safety requirements of the IAEA Transport Regulations in combination with the safety level of rail and road transportation lead to a good safety level concerning waste transports of primarily LSA-materials.

The procedure of probabilistic source term determination, formation of source term groups and the derivation of a limited number of representative release categories have been described. How source term groups were generated has been explained referring to Figs. 3.1 and 3.2. Input to this part of the analysis were radiological hazard indices for the various radionuclides, which were used to construct a cumulative complementary frequency distribution (ccfd) of the radiological hazard index of the Monte Carlo generated source terms. In Fig. 5.2 the ccfd of radiological hazard index (relative units) is compared with the actual shape of the ccfd of expected frequencies of effective doses (at 250 m) from Fig. 5.1. It can be concluded that the ccfd of the radiological hazard index compares quite well with the shape of the ccfd of effective doses. This can be interpreted as supporting the consistency of the procedure to reduce a large number of generated source terms to a limited number of representation release categories for further analysis of radiological consequences.

6 Literature

H.J. Fett, F. Lange: Analysis of German Rail Accident Statistics for Risk Assessment, PATRAM '92 Symposium, (September 1992) Yokohama, Japan

D. Gründler, G. Philip, W. Wurtinger: Probabilistic Source Term Determination (PSTD), 1991 Joint International Waste Management Conference, Volume 1, (Intermediate Level Radioactive Waste Mangement) p. 293-296, 21-23 Oct. 1991, Seoul, Korea

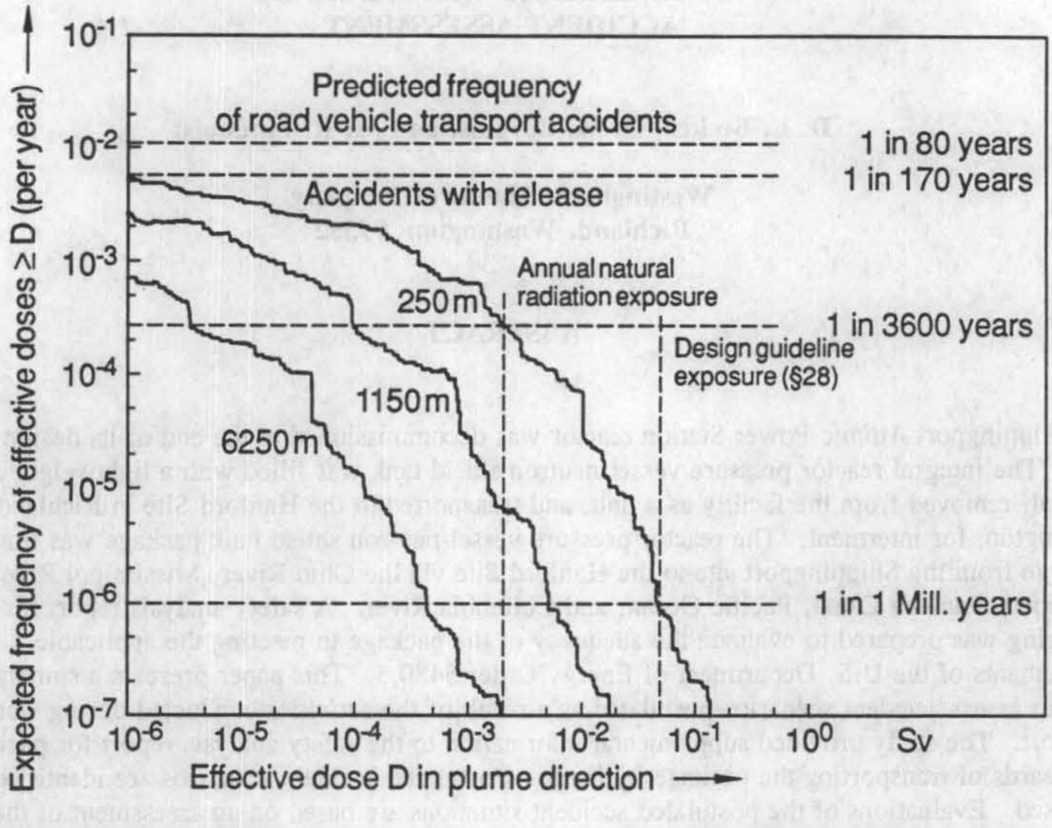

Fig. 5.1: Frequency distribution of the effective lifetime dose from waste transport accidents in the region (25 km zone) of the KONRAD waste repository. (20% road transport)

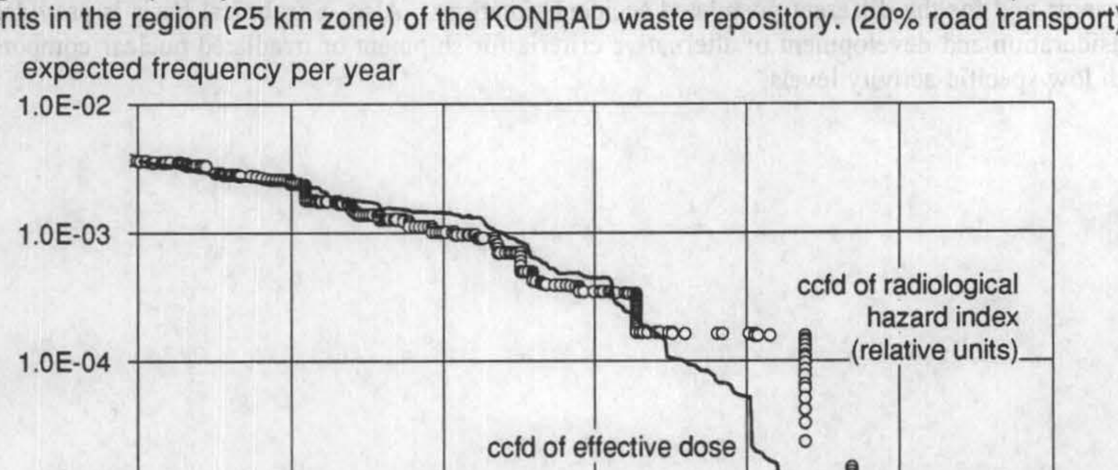

Fig. 5.2: Comparison of ccfd of expected effective dose (cf Fig. 5.1, 250 m) with ccfd of radiological hazard index (cf Fig. 3.1)