NUREG/CR-6672: PROBABILITY DISTRIBUTIONS DEVELOPED FOR IMPORTANT PARAMETERS EMPLOYED IN THE RADTRAN 5/LHS INTERFACE

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ABSTRACT

The construction of cumulative distributions of values for RADTRAN variables that take on a wide range of values in the real world is described. Where adequate data existed, probability distribution functions were constructed for important RADTRAN input parameters. Values obtained by structured Monte Carlo sampling (Latin Hypercube Sampling) from these distributions were used to construct RADTRAN input files.

Among the distributions of important variables that could be developed were: route characteristics (population densities, length, and rural, suburban and urban fractions), truck and rail accident rates, truck stop time, post-accident evacuation time, atmospheric stability category, dose rate at one meter, and highway traffic density and vehicle occupancy

As an example, methods and derivations for rail-mode data, and the RADTRAN calculations performed with these input values, will be presented. The number of LHS samples needed to obtain a representative, stable, random sample for use in risk calculations is also discussed.

INTRODUCTION

A wide variety of shipment conditions is addressed in NUREG/CR-6672 [1]. Many of the RADTRAN input parameters have a wide associated range of values. Where adequate data existed, probability distribution functions were constructed to define parameter values over their respective ranges. Values obtained by structured Monte Carlo sampling (Latin Hypercube Sampling) from these distributions were then incorporated into RADTRAN input files. Use of probability distributions rather than conservative point-estimates greatly reduced the number of RADTRAN calculations required, constrained conservatism, improved accuracy, and provided explicit representation of the variability of calculated doses and risks.

Incident-free transport parameters and hypothetical accident parameters in RADTRAN were divided into two groups: Important Variables and Less Important Variables. Important Variables strongly affect consequence and risk calculations, while Less Important Variables impact consequence and risk values only slightly. Central estimate values were selected for the Less Important Variables. Although radiation doses are strongly affected by changes in the value of any Important Variable, not all Important Variables take on a wide range of values in the real world.

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Thus, Important Variables were subdivided into two groups, those with values that are constant or that vary only slightly, and those with a wide range of values.

This paper describes the development of cumulative distribution functions to represent the latter class - Important Variables with a wide range of values, mainly for variables that are important for spent fuel transport by rail.

ROUTE CHARACTERISTICS

Since interim storage and permanent repository sites, and exact routes to these sites have not yet been officially selected, cumulative distributions were developed for route parameters so that a representative set of routes could be constructed by Latin Hypercube Sampling from these distributions. Provided that the distributions represent the full spectrum of possible routes and that sufficient sets of RADTRAN input variables are analyzed, the calculated risk means and standard deviations will accurately represent the risks associated with real shipments whenever they actually take place. Six locations for possible interim storage sites were selected, one in each sixth of the continental U.S. The HIGHWAY [2] and INTERLINE [3] routing codes were used to construct routes between these sites and the present locations of spent fuel (mainly commercial reactor sites). Routes were also constructed that connected these six possible interim storage sites to the Yucca Mountain site and to two alternate permanent repository sites. This process generated 450 possible truck or rail shipment routes. Histograms and cumulative distributions of the route lengths, the rural, suburban and urban route-length fractions, and the rural, suburban, and urban route wayside population densities were constructed to support the development of a representative set of routes by Latin Hypercube Sampling [4] from these distributions.

Route Lengths

Route length is a key parameter of accident probability, which is the product of accident rate (number per vehicle-km) and length. Furthermore, incident-free doses are proportional to route length and to route-length multiplied by population-density (populations sharing and neighboring the route). A histogram of route lengths derived from the route database is presented in Figure 1. Integration of this histogram and normalization to a total cumulative probability of 1.0 yields the desired route-length distribution shown in Figure 2.

Rural, Suburban and Urban Route Fractions

The same route database provided values for the aggregate fractions of each route traversing areas of Rural, Suburban or Urban population density. The population densities corresponding to these RADTRAN categories are defined in Table 1.

Table 1 Definition of Population Density Categories (persons/km^2)

Category	Minimum	Maximum	Mean
Rural	0	66	6
Suburban	67	1670	719
Urban	1670	Unlimited	3861

Figure 1 Histogram of Route Lengths

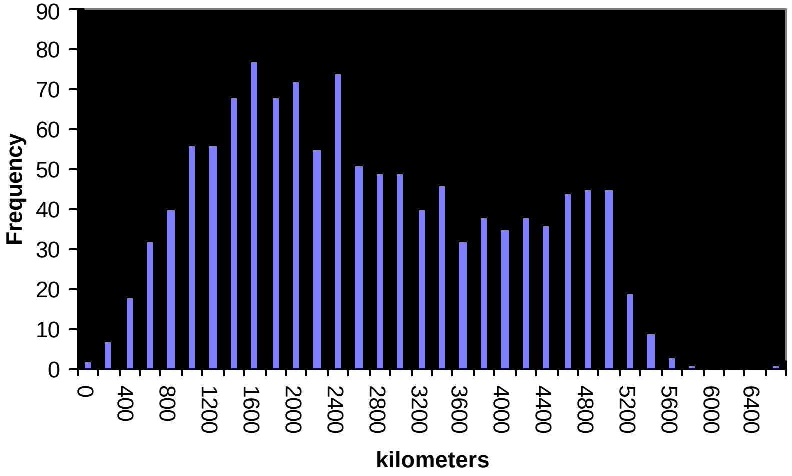


Figure 2 Cumulative Distribution of Route Lengths

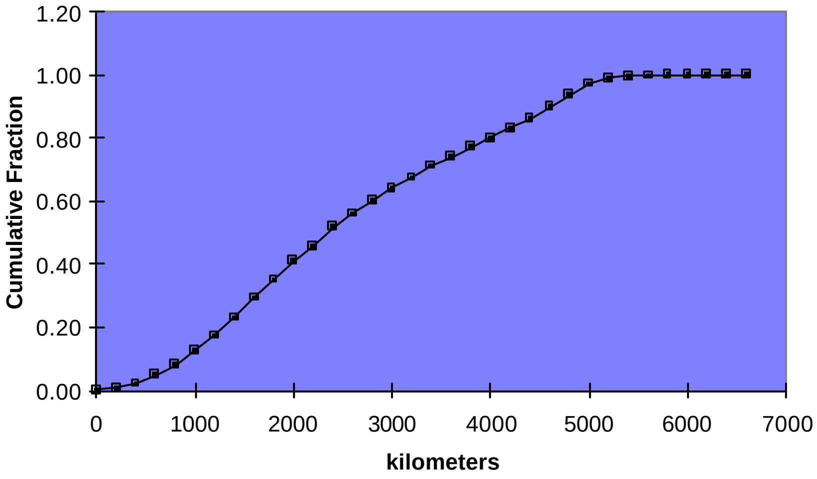


Figure 3 Cumulative Distributions of Rural, Suburban and Urban Fractions

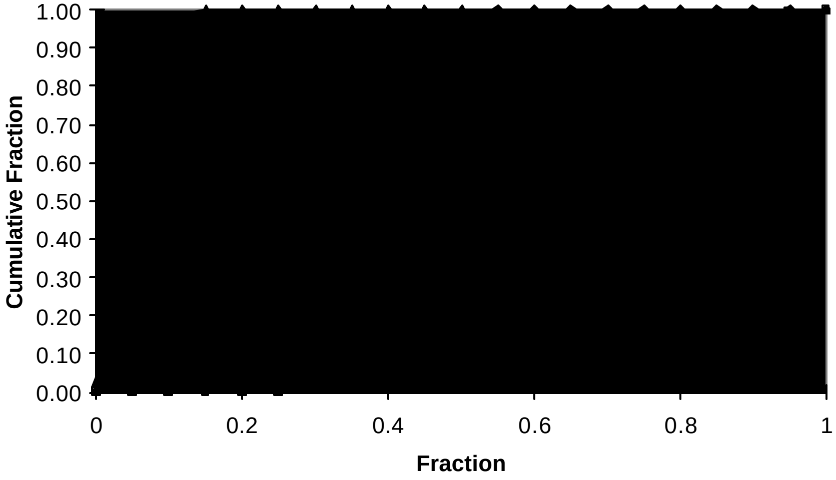
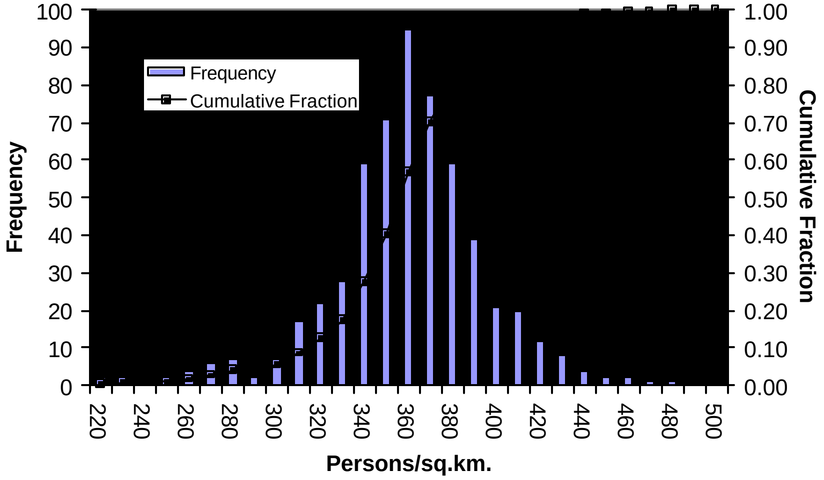


Figure 4 Histogram and Cumulative Distribution for *Suburban Population Density*



Histograms of the Rural, Suburban and Urban fractions, tabulated from the route database were constructed to create the cumulative distribution functions shown in Figure 3 by the same process as before.

Rural, Suburban and Urban Population Densities

The distance-weighted average population density values for rural, suburban and urban categories also were tabulated in the route characteristics database. Values were sorted and aggregated, then integrated and normalized to create histograms and cumulative distributions of population densities. As an example, the Suburban results are shown in Figure 4.

ACCIDENT RATES

Sources of accident-rate data for rail transport are tabulated in Table 2 together with their respective values.

Table 2 Rail Accident Rates

Source	Date	Urban or Total*	Comments
NUREG-0170 [5]	pre-1975	0.9E-6	Per Car km
Modal Study [6]			
(Fed. Rail Admin.)	1975-82	7.5E-6	Per Train km All trains & tracks
ANL Long. Rev.**	1985-88	0.06E-6	Per Car km, All tracks
[7, 8]		0.03E-6	Per Car km, Main Line Only

* Urban rate if distinguished, otherwise Urban and Non-Urban rate combined

** Average over 48 states

Note that the rate from the Modal Study is per *train*-km and must be corrected to car-km for comparison to the other values. Comparing car-miles to train-miles on Class I railroads for 1980 and 1990, as obtained from the DOT Internet Web page, indicated that the approximate number of cars per train is 68. This value leads to a Modal Study accident rate of 0.11E-6 per car-km, lying between the NUREG-0170 and ANL values.

A histogram and cumulative distribution of data for accidents on main lines by state, as compiled in the ANL study, were computed; the distribution is shown in Figure 5. The ANL study did not account for population density; therefore, this distribution was sampled by LHS to provide accident rates for all portions of the rail routes.

MISCELLANEOUS PARAMETERS

In addition to route parameters (length, population zone fractions, population densities) and accident rates, several additional parameters were selected as suitable for LHS.

Evacuation Time

The elapsed time between an accident and the completed evacuation of the area around an accident site was originally set at a very conservative 24 hours. More recent studies [9, 10] of evacuation times provided a distribution of times required to evacuate an accident area. A cumulative distribution was constructed from the data and was found to fit a log-normal distribution with high precision (Figure 6). This log-normal distribution was incorporated into the LHS input files used in the NUREG/CR-6672 risk calculations.

Figure 5 Cumulative Distribution of Rail Accident Rates

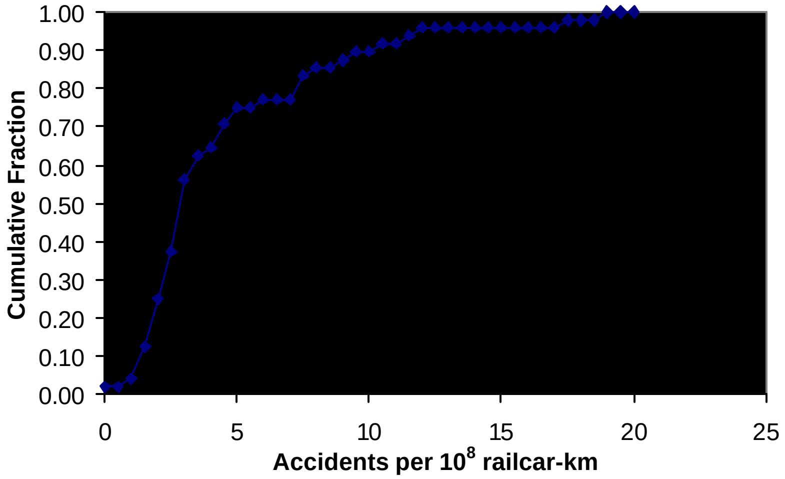
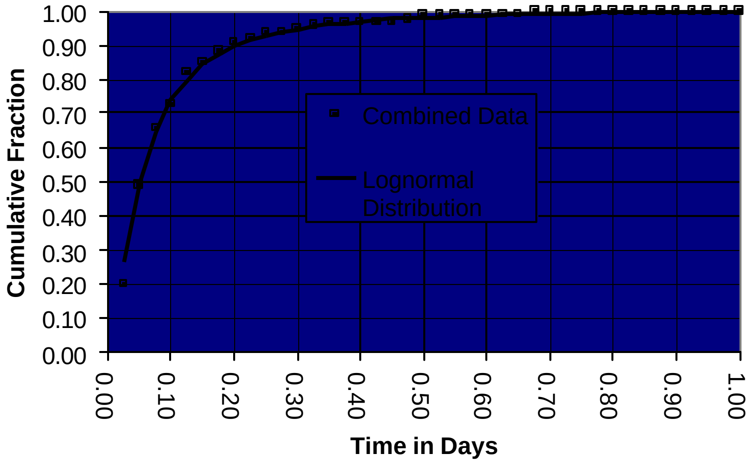


Figure 6 Distribution of Evacuation Times



Pasquill Category

A discrete cumulative distribution was used to select one of the six Pasquill atmospheric stability categories to be applied in each LHS set of RADTRAN input parameters; the weighting of each category in this distribution was based on average weather (stability conditions) in the United States [11]. This is appropriate because the site of a transportation accident cannot be pre-determined nor can the atmospheric stability at a random point be specified by measurements available from a (distant) weather station. This approach is less conservative than choosing the Pasquill category that leads to the highest doses as a fixed point-estimate. The normalized frequencies of categories and their cumulative distribution in Table 3 was used as LHS input.

Table 3 Distribution of Pasquill Categories

Pasquill Category	1	2	3	4	5	6
Cumulative Distribution	0.043	0.233	0.423	0.639	0.880	1.000

Vehicle Dose Rate

Maximum dose rate at 1 meter from the railcar (approximately equal to the dose rate 1 meter from the cask) is identified as the vehicle dose rate (DR) in RADTRAN 5 input and is essential to the calculation of incident-free doses. A study of calculated dose rates versus distance from a rail cask containing spent fuel of various cooling times was published previously [12]. The doses calculated for a distance of 1 meter from the cask, containing spent fuel cooled for 3 to 25 years, were correlated with a tabulation of numbers of assemblies versus years of cooling (number of assemblies having the specified cooling time) for the PWR fuel currently in cooling pools at nuclear plants [13]. For purposes of conservatism in addressing future casks of unknown specific design, the calculated dose rates at 1 meter were scaled (maximum of 13 mrem/hr at 1 meter) to give a maximum of 10 mrem/hour at 2 meters from the cask (the regulatory limit) for casks of approximately 5 meters maximum dimension. The cumulative distribution for PWR spent fuel was constructed by this method for a rail cask (Table 4).

Table 4 Distribution of Dose Rate at 1 meter (TI) for Rail

Cooling Time (yr.)	***TI***	PWR		***Distribution Applied in Calculations***
		Assys. of that Age	Cumulative Distribution	
3	**13.0**	1400	1.000	**1.00**
5	**6.72**	2824	0.875	**0.87**
10	**3.95**	2785	0.622	**0.63**
15	**3.03**	1937	0.373	**0.38**
20	**2.43**	1662	0.200	**0.21**
25	**1.99**	575	0.051	**0.08**

STATISTICAL SUFFICIENCY

Application of the Latin Hypercube Sampling method must be demonstrated to yield parameter values that satisfactorily cover the range of the sampled distributions. Accident-risk values calculated by RADTRAN for increasing numbers of LHS observations were tabulated and compared with random statistical variations resulting from changes of the random-number-generator "seed". Table 5 presents average, standard deviation, etc. of total accident risk with the indicated number of observations; Table 6 lists the results from changes in the "seed".

Table 5 RADTRAN/LHS Accident-Risk Results versus Number of Observations

Observations	100	200	300	400	500
Average	2.73E-7	2.87E-7	**2.90E-7**	2.82E-7	2.86E-7
Standard Dev.	2.45E-7	2.83E-7	**3.06E-7**	2.94E-7	2.85E-7
Maximum	1.13E-6	1.79E-6	1.70E-6	**2.34E-6**	2.00E-6
Minimum	5.3E-9	1.68E-9	3.42E-9	2.70E-9	**1.14E-9**

Extremes in each category are shown in Bold type.

Table 6 RADTRAN/LHS Accident-Risk Results for 200 Observations versus "Seed"

Seed Selection	#1	#2	#3	#4	#5
Average	2.87E-7	**2.96E-7**	2.80E-7	2.85E-7	2.78E-7
Standard Dev.	2.83E-7	**3.20E-7**	2.89E-7	3.13E-7	2.70E-7
Maximum	1.79E-6	1.64E-6	1.71E-6	**1.92E-6**	1.38E-6
Minimum	1.68E-9	4.17E-9	4.40E-9	**8.88E-11**	4.47E-9

Extremes in each category are shown in **bold** type.

Inspection of Table 5 indicates that increasing the size of the LHS sample above 200 did not significantly improve the precision of the resulting estimates of risk (e.g., the average and standard deviation for the sample of size 500 are almost identical to the values obtained for the sample of size 200). Table 6 shows that the risk results calculated with LHS samples of size 200 do not vary significantly when the random seed is changed. This means that the results presented in NUREG/CR-6672 would not have been significantly changed if more LHS observations had been employed.

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