Application of Latin Hypercube Sampling to RADTRAN 4 Truck Accident-Risk Sensitivity Analysis

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INTRODUCTION

The transportation risk analysis code, RADTRAN 4 (Neuhauser and Kanipe 1992), computes estimates of incident-free dose consequence and accident dose-risk. The output of the code includes a tabulation of sensitivity of the result to variation of the input parameters for incident-free analysis. Values are calculated using closed mathematical expressions derived from the constitutive equations, which are linear. However, the equations for accident risk are not linear, in general, and a similar tabulation has not been available. Because of the importance of knowing how accident-risk estimates are affected by uncertainties in the input parameters, a direct investigation was undertaken of the variation in calculated accident dose-risk with changes in individual parameters. A limited, representative group of transportation scenarios was used, initially, to determine which of 23 accident-risk parameters affect the calculated accident dose-risk significantly (Mills et al. 1995). Many of the parameters had minimal effect on the output, and others were "fixed" either by regulation, convention, or standards. The remaining 5 input arrays were selected for further study through Latin Hypercube Sampling (LHS) (Iman and Shortencarier 1984). The use of LHS yields statistical information about risk calculations by providing multiple input-parameter sets, compiled from "random" sampling of parameter distributions, for multiple RADTRAN calculations. The LHS method requires fewer observations than classical Monte Carlo methods to yield statistically significant results. This paper summarizes the preliminary parameter study and LHS application results to date, in addition to presenting the results of subsequent studies of RADTRAN input parameter distributions and their effects on risk estimate uncertainty.

ANALYSIS

RADTRAN calculations of accident risk were carried out for transportation scenarios developed either from actual experience or for special cases to emphasize a parameter of interest (e.g., nondispersal accidents). The baseline values used in this study were adapted from archived input files supporting published Sandia analyses of shipments of spent nuclear fuel and other materials by highway over a variety of routes. These analyses included six-category and eight-category accident-severity schemes and both Type A and B packages, which provided suitable breadth of application. Relationships between various possible severity schemes and characteristics of package types are discussed elsewhere (U. S. CFR 49 1992; Whitlow and Neuhauser 1993).

Previously (Mills et al. 1995; Mills and Neuhauser 1995), four of the parameters identified as suitable for LHS analysis were investigated: Release Fractions (RFRAC), Pasquill Category Weights (PSPROB), Link Population Densities (LPOPD), and Link Accident Rates (LARAT). These past investigations revealed that the use of rather broad distributions for these parameter sets did not yield unacceptable uncertainty in the resultant risk estimates whether all of the parameters were varied singly or in combination (i.e., independent LHS of all four parameter sets) (Mills and Neuhauser 1995). The distributions employed in these previous studies were defined somewhat arbitrarily for purposes of illustration; in the work reported here, available data were used to define distributions related to actual transportation experience.

Definition of Parameter Distribution Functions

Use of LHS requires definition of probability distributions for each variable of interest.

Highway Accident Rates - In the case of accident rates (LARAT), results presented previously (Mills et al. 1995; Mills and Neuhauser 1995) were developed with normal distributions with means set equal to the averages, over all 48 States in the continental United States, of accident rates for each of four highway types. The value of σ for each distribution was set to approximately the same fraction of the mean as the standard deviation of each average (approximately 50% or 100%). When risk estimates are required on a State-by-State basis, the individual State accident rates are employed. In order to estimate the uncertainty of these values, the variation of the national accident rate for motor carriers of property, as derived from DOT compilations, for the years 1965 through 1990 at 5-year intervals plus 1991 was analyzed. The standard deviation of these accident rates relative to their mean was ±54%, which is comparable to the State-to-State variations. In order to maintain conservatism in analyses, the standard deviation of normal distributions used to describe accident rates in current and future risk uncertainty calculations was defined to be ±100%.

Link Population Densities - For link population densities, normal distributions with standard deviations of ±25% were employed previously. However, the point estimates obtained from census data via the HIGHWAY routing code (ORNL 1992) suffer from three known sources of error: (1) population density adjoining a highway segment is related to the average value within the corresponding census tract, which may extend substantially beyond the 0.8 km either side of the highway, (2) the data are coarsely aggregated to 1 km square grid cells before they are related to segments, and (3) census data describe where people reside, not where they are located at arbitrary times of the day. In view of the uncertainty implied by these potential errors, we examined the effects on risk-estimate uncertainty of increasing standard deviations to ±100% and the use of uniform distributions rather than normal distributions.

Package Release Fractions - Previously, release fractions (RFRAC) were defined by loguniform distributions, which concentrate samples (compared to uniform distributions) at the lower end of the range of parameter values. While this conforms with the overall relationship of consequence to probability (i.e., greatest consequence has the lowest probability), use of uniform distributions provides more conservative analysis. Therefore, analyses using both types of distributions were performed in the current study to broadly assess the net effect on risk uncertainty.

Differences Based on Package Types

Two distinct truck transportation cases were used to compare these alternative parameter descriptions: shipment of multiple Type A packages over a route of recent interest to Sandia, and shipment of spent nuclear fuel in a typical cask over a route that is used as a standard in evaluating updates to the RADTRAN code. In the first case, an eight-level scheme is used to define the spectrum of accident severities; for Type A packagings, accidents having severities in the highest four categories are expected to result in 100% release and the RFRAC values were set to 1.0. The range of fractional releases of the lowest four severity categories, 0.0 to 1.0, was broken into decades: 0.0 to 0.001, 0.001 to 0.01, 0.01 to 0.1, and 0.01 to 1.0. These ranges take into account the fact that not all of the packages are affected in lower severity accidents and also includes a remote possibility of release in the lowest severity category, which regulation requires to be zero.

In the second case, a six-level scheme defined for spent-fuel cask transport was modified to describe the spectrum of accident severities while taking advantage of simplification made possible by LHS. Table 1a lists the severity fractions for rural, suburban, and urban environments and the corresponding release fractions of the different physical/chemical groups of isotopes in spent nuclear fuel. As can be seen from the table, the three lowest-severity category fractions sum to 0.9999 or more, and the three highest-severity categories represent only 0.000015 or less of all accidents. Because of their relatively minute probability, the three highest-severity fractions were summed to reduce the scheme to four levels of severity (Table 1b). The progressive increases in release fraction values were modeled by appropriate choices of LHS distribution functions.

Note that the first physical-chemical group corresponds to CRUD, a scale (primarily cobalt 60) which builds up on the exterior of the fuel cladding during pool storage and can be released in a Category 3 accident. The other isotope groups are only released in accidents sufficiently severe to compromise the fuel cladding as well as the cask. Because the (severity) fraction of Category 3 accidents is much larger than the sum of all more severe accidents, CRUD-release generally dominates the accident-risk of such shipments.

Table 1a. Baseline Accident Severity Fractions and Release Fractions for Spent Nuclear Fuel in Casks

Severity Fractions						
	Severity 1	Severity 2	Severity 3	Severity 4	Severity 5	Severity 6
Rural	0.603	0.394	0.003	3.0E-6	5.0E-6	7.0E-6
Suburban	0.602	0.394	0.004	4.0E-6	3.0E-6	2.0E-6
Urban	0.604	0.395	3.8E-4	3.8E-7	2.5E-7	1.3E-7
Release Fractions						
Group 1*	0.0	0.0	0.012	0.012	0.012	0.012
Group 2	0.0	0.0	0.0	0.01	0.10	0.11
Group 3	0.0	0.0	0.0	1.0E-8	2.0E-4	2.8E-4
Group 4	0.0	0.0	0.0	1.0E-8	5.0E-8	5.0E-8
Group 5	0.0	0.0	0.0	1.0E-8	1.0E-6	4.2E-5

* CRUD - Scale on exterior surface of fuel cladding.

Table 1b. Accident Severity Fractions and Release Fractions (4-level) for Spent Nuclear Fuel in Casks used in Sample Calculations

Severity Fractions				
	Severity 1	Severity 2	Severity 3	Severity 4
Rural	0.603	0.394	0.003	1.5E-5
Suburban	0.602	0.394	0.004	9.0E-6
Urban	0.604	0.395	3.8E-4	7.6E-7
Release Fractions				
Group 1*	0.0	0.0	0.012	0.012
Group 2	0.0	0.0	0.0	0.11
Group 3	0.0	0.0	0.0	2.8E-4
Group 4	0.0	0.0	0.0	5.0E-8
Group 5	0.0	0.0	0.0	4.2E-5

* CRUD - Scale on exterior surface of fuel cladding.

Contribution of Urban Links to Total Risk

Stakeholders are typically very interested in risks to high-population-density (urban) areas along transportation routes. The relative insignificance of these route segments in the calculation of total risk associated with typical transportation routes was demonstrated when the urban component of the risk for shipment of spent-fuel casks, described above, was determined. Table 2 presents the pertinent parameters of the route and the accident-risk values for the total route together with the risk for the urban links alone. The route traverses most of the continental United States (East to West) from Florida to Washington State and is predominantly rural, as one might expect. For comparison, a route that traverses one of the most urbanized areas in the Nation, from Boston, MA, to Lynchburg, VA, was also examined in a similar manner; the results are presented in Table 2.

Table 2. Comparison of Urban to Total Risks for Two Routes

Crystal River, FL to Hanford, WA						
Total Distance	Urban Dist.	% Urban	Total Risk	Std. Dev.	Urban Risk	Urban/Total
4905 km	68 km	1.4	0.029	56%	8.9E-4	3.1%
Boston, MA to Lynchburg, VA						
Total Distance	Urban Dist.	% Urban	Total Risk	Std. Dev.	Urban Risk	Urban/Total
1093 km	116 km	10.6	0.020	108%	2.0E-3	10%

CONCLUSIONS

The example calculations presented in this paper, like those in previous presentations (Mills et al. 1995; Mills and Neuhauser 1995), reveal that risk-estimate uncertainties are smaller than the conservatively broad distributions employed for the input parameters. This is true for all cases in which values for several parameters are generated from independently sampled distributions, e.g., allowing all six Pasquill class weights to vary over their full ranges yields risk estimates with Standard Deviations of only 20% or less (Tables 3 and 4). In contrast, calculations using each class singly vary more than a factor of 10. However, if a broad distribution is used to describe a highly dominant variable, e.g., the release fraction for CRUD in spent nuclear fuel shipments (loguniform case in Table 4), Standard Deviation of the resultant risk estimate can be substantial, e.g., 236%. This latter example illustrates a problem that can arise in the use of the loguniform distribution: samples have a smaller mean (compared to that of a uniform distribution), but the standard deviation will be excessive if the distribution spans multiple decades. As a consequence of these findings, we conclude that critical variables in a specific analysis must be modeled with caution and simplifications such as the combination of severity fractions (Tables 1a and 1b) may lead to complexity in the choice of distributions.

The results presented in Table 2 clearly illustrate the point that the urban segments of nearly all routes that might be traversed in typical shipments of radioactive materials in the

Table 3. Results for Type A Package Transport

Variable(s)	Distribution Type	Range or Std. Dev.	Average Risk	Risk Std. Dev.
PSPROB*	Uniform	➔ 0.0 to 1.0	2.6E-5	16%
LARAT	Normal	±50%	2.6E-5	30%
		➔ ±100%	3.3E-5	38%
LPOPD	Normal	±25%	2.6E-5	19%
		±100%	3.3E-5	32%
	Uniform	➔ 0% to 200%	2.6E-5	31%
RFRAC	LogUniform	➔ 1E-9 to 1E-3 to 1E-2 to 0.1 to 1.0	2.1E-5	33%
	Uniform	1E-9 to 1E-3 to 1E-2 to 0.1 to 1.0	2.8E-5	28%
Cases Marked "➔" Combined			2.3E-5	52%

*The Pasquill Weights were sampled in conjunction with each of the other variables.

Table 4. Results for Spent Nuclear Fuel Cask Transport

Variable(s)	Distribution Type	Range or Std. Dev.	Average Risk	Risk Std. Dev.
PSPROB*	Uniform	➔ 0.0 to 1.0	0.044	19%
LARAT	Normal	±50%	0.045	40%
		➔ ±100%	0.054	50%
LPOPD	Normal	±25%	0.044	28%
		±100%	0.056	52%
	Uniform	➔ 0% to 200%	0.044	50%
RFRAC	LogUniform	1E-9 to Sev. 3# or 4 Values in Table 3b	0.0032	236%
	Uniform	➔ 1E-9 to Sev. 3# or 4 Values in Table 3b	0.023	56%
Cases Marked "➔" Combined			0.029	95%

*The Pasquill Weights were sampled in conjunction with each of the other variables.
Group 1, CRUD.

continental United States contribute very little to the risk associated with the shipment, especially compared to the uncertainty of the total risk estimate. This is true even for a route that maximizes the fraction of highway distance passing through areas of urban population density. Note that the relatively large uncertainty in the Boston-to-Lynchburg case is a result of only two links (one suburban and one urban) contributing most of the risk. If this uncertainty were reduced by half, the urban fraction of the risk would nevertheless be small in comparison.

The efficiency of the Latin Hypercube Sampling technique makes explicit calculation of the sensitivity of risk values to input parameter variations a reasonable approach to accident-risk analysis. Substantial uncertainty in critical input parameters, such as release fractions, may be addressed more realistically by application of a maximum (minimum) parameter value as the upper (lower) limit of an appropriate distribution with a resultant reduction (increase) in the average risk estimate while the corresponding uncertainty in the result is determined explicitly.

Further investigation of the effects of uncertainties in RADTRAN input parameters will concentrate on aspects of radioactive material transport that require research effort to improve parameter definition. Research decisions must be guided by the difficulty (cost) of improved definition compared to the net effect on uncertainty of risk estimates.

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