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

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ABSTRACT

The sensitivity of calculated dose estimates to various RADTRAN 4 inputs is an available output for incident-free analysis because the defining equations are linear and sensitivity to each variable can be calculated in closed mathematical form. However, the necessary linearity is not characteristic of the equations used in calculation of accident dose risk, making a similar tabulation of sensitivity for RADTRAN 4 accident analysis impossible. Therefore, a study of sensitivity of accident risk results to variation of input parameters was performed using representative routes, isotopic inventories, and packagings. It was determined that, of the approximately two dozen RADTRAN 4 input parameters pertinent to accident analysis, only a subset of five or six has significant influence on typical analyses or is subject to random uncertainties. These five or six variables were selected as candidates for Latin Hypercube Sampling applications.

To make the effect of input uncertainties on calculated accident risk more explicit, distributions and limits were determined for two variables which had approximately proportional effects on calculated doses: Pasquill Category probability (PSPROB) and link population density (LPOPD). These distributions and limits were used as input parameters to Sandia's Latin Hypercube Sampling code to generate 50 sets of RADTRAN 4 input parameters used together with point estimates of other necessary inputs to calculate 50 observations of estimated accident dose risk.

Tabulations of the RADTRAN 4 accident risk input variables and their influence on output plus illustrative examples of the LHS calculations, for truck transport situations that are typical of past experience, will be presented .

INTRODUCTION

The transportation risk analysis code, RADTRAN 4 [Neuhauser, 1992], computes estimates of incident-free dose consequence and accident dose risk. The output of the code can include a tabulation of sensitivity of the result to variation of the input parameters for the incident-free analysis. The 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. It is, nevertheless, important to know how the accident risk is affected by uncertainties in the input parameters. A direct investigation of the variation in calculated accident dose-risk with changes of individual parameters was undertaken. Initially, a limited, representative group of transportation scenarios was used to determine which of 23 accident-risk input parameters or arrays affect the calculated accident dose risk significantly. Many of the parameters were observed to have minimal effect on the output while others were judged as "fixed" either by regulation, convention or standards. The remaining 5 input arrays were selected for further study through Latin Hypercube Sampling (LHS) [Iman, 1984]. LHS

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yields statistical information from observations (risk calculations) resulting from multiple input parameter sets compiled from "random" sampling of cumulative probability distributions. The LHS method requires fewer observations than classical Monte Carlo methods to yield statistically significant results. This paper presents the preliminary input parameter studies and their results together with some initial LHS investigations.

ANALYSIS

A list of the RADTRAN 4 input parameters and arrays employed in accident-risk calculations was compiled and is presented in Table I. RADTRAN calculations of accident risk were performed for transportation scenarios drawn from actual experience or special cases designed to emphasize a parameter of interest (e.g., non-dispersal accidents). The baseline values used in this study were adapted from archived input files supporting published Sandia analyses, e.g., shipment of spent nuclear fuel by highway from Norfolk, VA to the Savannah River Site, SC. Actual input files used in the examples presented here are listed in the Appendix. Either eight-category or six-category accident-severity schemes are typically employed in RADTRAN analyses depending on the specific isotopes being shipped and the type of packaging used. Thus, the SEVFRC (all parameter names are defined in Table I) arrays in the test files have six or eight baseline values for each population density category (rural, suburban, urban). The RFRAC, AERSOL, and RESP arrays have six- or eight-element arrays defined for each physical-chemical group (only 1 in the examples listed in the Appendix) required to describe the materials being shipped. Relationships between various possible severity schemes are discussed in Whitlow and Neuhauser, 1993.

The results of discrete calculations, in which values other than the RADTRAN-supplied value for a particular input parameter were tried are listed in Table II. The "Results" are values of the "Total" accident dose-risk calculated by RADTRAN 4. Although some of the input variables listed had a larger effect on component risks such as the "Urban", "Inhaled" and "Resuspended" dose-risks, the "Total" risk is the value most often quoted in applications of RADTRAN 4 analyses. Therefore, it is the basis for sensitivity evaluations reported here. Current practice in reporting results has been to tabulate values to two significant digits, in keeping with the uncertainties of the analysis.
Discussion of each of the five input variables and the test calculation results listed in Table II follows:

BRATE (breathing rate) -- The suggested point estimate is based on the maximum rate for humans and a reduction to half of that value did not change the risk estimate.

BDF (fraction of respirable aerosol inside buildings) -- Changes of a factor of 10 up and down yielded the same results as the point estimate.

RPD (ratio of pedestrian to resident population density) -- An increase by a factor of two resulted in the slightest reportable change in the result: 2.7E-08 to 2.8E-08.

RU (Urban building shielding factor) -- As noted in Table I, it only affects accident risk results in cases of non-dispersal accidents. The calculated change in risk (3.0E-11 to 3.1E-11) occurred for an increase of RU by a factor of 10.

CULVL (cleanup level) -- This has a significant effect on calculated risk upon being lowered by a factor of 10, but such a change in regulations is not presently known or expected.

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In summary, none of these five input parameters was included in subsequent LHS analysis since, for reasonable distributions of their values, their effects on risk calculations would be hidden by the effects of other input parameters or arrays.

Some of the variables listed in Table I were not subjected to these tests because they were viewed as not being subject to random uncertainties, or clearly would affect output significantly (proportionally). The list of input parameters and arrays from Table I and the sensitivities of total risk to them, are presented in Table III together with an indication of which (five input arrays) should be studied further with LHS.

To date, two of the input arrays identified in Table III as suitable for LHS analysis have been investigated through use of LHS in conjunction with RADTRAN calculations: Pasquill Category Weights (PSPROB) and Link Population Densities (LPOPD). These inputs were selected for initial study because justifiable distributions of their values could be estimated easily and because LPOPD and PSPROB array sizes are not affected by the choice of accident-severity scheme. Accident-severity and related variables are to be addressed in the future.

Use of LHS requires definition of probability distributions for each variable of interest. In the case of the six Pasquill Stability Class variables (PSPROB array), a uniform distribution between 0.0 and 1.0 for each of the six classes was sampled independently and the sum of each set of six samples was normalized to 1.0, as required by RADTRAN 4. For the link population densities (LPOPD values) normal distributions centered on the point estimates for each of the links describing a particular route were used. The widths of the normal distributions were chosen such that σ (standard deviation parameter of the normal distribution function), was 10% of the mean for one set of calculations and 25% of the mean for a second set of calculations.

Table IV summarizes the results from 50 observations (RADTRAN accident-risk calculations) employing 50 samples from either the PSPROB or one of the LPOPD distributions in the input files. Also, Table IV includes results from calculations employing 50 samples from the PSPROB and one of the LPOPD distributions, together, in the input files. The risk value calculated for the same transportation scenario without LHS, 5.32E-05 person-rem, is higher than values for the three cases in which PSPROB values were varied. This is because the default set of PSPROB values in RADTRAN leads to a more severe dispersion situation than the "random" mix of all six conditions. When each Pasquill category was applied individually, the results varied by more than a factor of 10.

CONCLUSIONS

The rather long list of input parameters and arrays required to calculate accident dose-risk estimates with RADTRAN 4 has been pared down to five arrays that have proportional effects on the estimate of total risk. A few additional input variables have proportional effects on component risks such as risk in urban areas or the respirable component, but negligible effect on the total risk. Use of Latin Hypercube Sampling on two of the input arrays, PSPROB (6 array elements) and LPOPD, revealed that quite reasonable selections of distribution type and limits yield risk estimates and uncertainties which are in accord with expectation based on the input array means and the randomness of the input values. In the case of Pasquill atmospheric stability classes, random mixes of the 6 class weights result in lower risk

estimates than those calculated with the RADTRAN 4 default set. Treating link population densities (LPOPD's) derived from the HIGHWAY [ORNL, 1992] routing code as normally distributed variables with ±25% standard deviation led to risk estimates having an average value equal to the risk estimate calculated without LHS; the standard deviation of the 50 risk estimates was ±11%.

Further studies of the rest of the input variables to which accident risk estimates were found to have proportional sensitivity must be investigated further, individually and in combinations, to determine the range of uncertainty to be expected in typical RADTRAN 4 accident dose risk calculations.

REFERENCES

Iman, R. L. and M. J. Shortencarier, "A FORTRAN Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models," NUREG/CR-3624, SAND83-2365, Sandia National Laboratories, Albuquerque, NM, March 1984.

Neuhauser, K. S. and F. L. Kanipe, "RADTRAN 4 - Vol. 3: User Guide," SAND89-2370, Sandia National Laboratories, Albuquerque, NM, January 1992.

ORNL (Oak Ridge National Laboratory), "HIGHWAY 3.1 - An Enhanced Highway Routing Model: Program Description, Methodology, and Revised User's Manual," ORNL/TM-12090, ORNL, Oak Ridge, TN 1992

Whitlow, J. D. and K. S. Neuhauser, 1993, "A Methodology for the Transfer of Probabilities between Accident Severity Classification Schemes," in Transportation of Dangerous Goods: Assessing the Risks, F. F. Saccomano and K. Cassidy, Eds., Institute for Risk Research, Waterloo, Canada.

APPENDIX

RADTRAN 4 input file listings.

Sample of RADTRAN input files used for evaluation of sensitivity to BRATE, BDF, RPD and CULVL:

```
&& _TRUCK_CASE_NORFOLK_TO_CHARLESTON_
FORM UNIT
DIMEN 1 6 1 10 18
PARM 1 3 2 1 0
PACKAGE
  LABGRP
    STUFF
SHIPMENT
  LABISO
    CO60
NORMAL
  NMODE=1
    1.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    2.000E+00 1.000E+01 0.000E+00 1.100E-02 0.000E+00 0.000E+00
    0.000E+00 5.000E+01 2.000E+01 0.000E+00 0.000E+00 0.000E+00
    2.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00
    0.000E+00
ACCIDENT
  SEVFRC
   NPOP=1
    NMODE=1
    6.23E-01 3.74E-01 3.00E-03 3.00E-06 5.00E-06 7.00E-06
   NPOP=2
    NMODE=1
    6.22E-01 3.74E-01 4.00E-03 4.00E-06 3.00E-06 2.00E-06
   NPOP=3
    NMODE=1
    6.24E-01 3.75E-01 3.80E-04 3.80E-07 2.50E-07 1.30E-07
RELEASE
  RFRAC
   GROUP=1
    0.00E+00 0.00E+00 2.50E-03 5.00E-02 7.50E-01 1.00E+00
  AERSOL
   DISP=5
    0.00E+00 0.00E+00 0.00E+00 1.00E+00 1.00E+00 1.00E+00
  RESP
   DISP=5
    0.00E+00 0.00E+00 0.00E+00 5.00E-02 5.00E-02 5.00E-02
OTHER
  BDF 8.600E-04
```

```
EOF
ISOTOPES 1   1    1.00   0.100  1.00  0.00 SAMPLE
      CO60 1.00E+00    STUFF  5
LINK  1 1.74E+01 8.86E+01 9.38E+00 4.70E+02 2.33E-07 R 1
LINK  1 2.90E+01 8.86E+01 5.62E+02 7.80E+02 2.33E-07 S 1
LINK  1 6.76E+00 4.80E+01 2.11E+03 2.80E+03 1.37E-07 U 1
LINK  1 8.06E+01 8.86E+01 1.16E+01 4.70E+02 4.23E-07 R 2
LINK  1 1.40E+01 8.86E+01 3.19E+02 7.80E+02 4.23E-07 S 2
LINK  1 1.34E+01 8.86E+01 1.10E+01 4.70E+02 2.33E-07 R 1
LINK  1 4.34E+00 8.86E+01 4.12E+02 7.80E+02 2.33E-07 S 1
LINK  1 2.25E+02 8.86E+01 1.61E+01 4.70E+02 2.30E-07 R 1
LINK  1 7.27E+01 8.86E+01 1.55E+02 7.80E+02 2.30E-07 S 1
LINK  1 2.21E+02 8.86E+01 1.65E+01 4.70E+02 1.61E-07 R 1
LINK  1 4.05E+01 8.86E+01 3.08E+02 7.80E+02 1.61E-07 S 1
LINK  1 7.08E+00 4.80E+01 2.13E+03 2.80E+03 3.16E-07 U 1
PKGSIZ
      SAMPLE    1.00
EOF
```

Special RADTRAN 4 input file used to evaluate sensitivity to RU (required an Urban, non-Interstate LINK *):

```
FORM UNIT
DIMEN 1 6 1 10 18
PARM 1 3 2 1 0
PACKAGE
  LABGRP
    STUFF
SHIPMENT
  LABISO
    CO60
NORMAL
  NMODE=1
    1.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
    2.000E+00  1.000E+01  0.000E+00  1.100E-02  0.000E+00  0.000E+00
    0.000E+00  5.000E+01  2.000E+01  0.000E+00  0.000E+00  0.000E+00
    2.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
    0.000E+00
ACCIDENT
  SEVFRC
   NPOP=1
    NMODE=1
    6.23E-01  3.74E-01  3.00E-03  3.00E-06  5.00E-06  7.00E-06
   NPOP=2
    NMODE=1
    6.22E-01  3.74E-01  4.00E-03  4.00E-06  3.00E-06  2.00E-06
```

```
    NPOP=3
     NMODE=1
     6.24E-01  3.75E-01  3.80E-04  3.80E-07  2.50E-07  1.30E-07
  RELEASE
   RFRAC
    GROUP=1
     0.00E+00  0.00E+00  2.50E-03  5.00E-02  7.50E-01  1.00E+00
  EOF
  ISOTOPES 1   1    1.00   0.100  1.00   0.00 SAMPLE
       CO60  1.00E+00    STUFF  1
  LINK  1 1.00E+03 8.86E+01 2.70E+01 4.70E+02 2.33E-07 R 1
  LINK  1 1.00E+02 8.86E+01 6.69E+02 7.80E+02 2.33E-07 S 1
  LINK  1 1.00E+02 4.80E+01 1.93E+03 2.80E+03 1.37E-07 U 1
  LINK  1 1.00E+01 4.80E+01 1.93E+03 2.80E+03 7.40E-06 U 2 *
  PKGSIZ
       SAMPLE    1.00
  EOF
```

Base RADTRAN 4 input file used in LHS calculations:

```
&& _Shipped_by_Truck_from_SNL/NM_to_NTS_
&& _Package_Dimension_Approximates_a_55gal_Drum_
TITLE _LABORATORY_WASTE_FROM_AREA_V _DRUM_
FORM UNIT
DIMEN 5 8 1 10 18
PARM 1 3 2 1 1
PACKAGE
  LABGRP
       A
SHIPMENT
  LABISO
    CS137    CS134    CE144     NB95     ZR95
NORMAL
  NMODE=1
     1.000E+00  0.000E+00  0.000E+00  8.856E+01  4.032E+01  2.416E+01
     2.000E+00  6.760E+00  0.000E+00  1.100E-02  0.000E+00  0.000E+00
     0.000E+00  5.000E+01  2.000E+01  0.000E+00  1.000E+02  1.000E+02
     2.000E+00  0.000E+00  0.000E+00  1.000E+00  4.700E+02  7.800E+02
     2.800E+03
```

```
ACCIDENT
  SEVFRC
    NPOP=1
      NMODE=1
      4.62E-01  3.02E-01  1.76E-01  4.03E-02  1.18E-02  6.47E-03
      5.71E-04  1.13E-04
    NPOP=2
      NMODE=1
      4.35E-01  2.85E-01  2.21E-01  5.06E-02  6.64E-03  1.74E-03
      6.72E-05  5.93E-06
    NPOP=3
      NMODE=1
      5.83E-01  3.82E-01  2.78E-02  6.36E-03  7.42E-04  1.46E-04
      1.13E-05  9.94E-07
RELEASE
  RFRAC
    GROUP=1
      0.00E+00  1.00E-02  1.00E-01  1.00E-01  1.00E+00  1.00E+00
      1.00E+00  1.00E+00
EOF
ISOTOPES -1   1    1.00   10.000   1.00   0.00 MTAP
      CS137  1.81E-01       A  7
      CS134  9.40E-03       A  7
      CE144  6.70E-02       A  7
       NB95  3.46E-02       A  7
       ZR95  1.90E-02       A  7
LINK  1 1.40E+00 2.42E+01 9.16E+02 7.80E+02 2.07E-07 S 2
LINK  1 1.80E+00 2.42E+01 2.68E+03 2.80E+03 7.40E-06 U 2
LINK  1 2.38E+02 8.86E+01 7.20E+00 4.70E+02 2.69E-07 R 1
LINK  1 2.01E+01 8.86E+01 4.98E+02 7.80E+02 2.69E-07 S 1
LINK  1 7.20E+00 8.86E+01 2.10E+03 2.80E+03 3.24E-07 U 1
LINK  1 4.74E+02 8.86E+01 1.70E+00 4.70E+02 2.60E-07 R 1
LINK  1 2.03E+01 8.86E+01 3.40E+02 7.80E+02 2.60E-07 S 1
LINK  1 1.60E+00 8.86E+01 2.14E+03 2.80E+03 2.81E-07 U 1
LINK  1 1.16E+02 8.86E+01 1.90E+00 4.70E+02 2.69E-07 R 2
LINK  1 1.17E+02 8.86E+01 3.00E+00 4.70E+02 4.51E-07 R 2
LINK  1 2.59E+01 8.86E+01 5.69E+02 7.80E+02 4.51E-07 S 2
LINK  1 1.47E+01 4.80E+01 2.46E+03 2.80E+03 4.51E-07 U 2
PKGSIZ
      MTAP    1.00
EOF
```

Table I. RADTRAN 4 Accident Risk Analysis Input Variables

RADTRAN Variable	Definition
SEVFRC	Fractions of Accidents Having a Given Severity
RFRAC	Fractions of Package Contents Released in an Accident of a Particular Severity
AERSOL	Fractions of Released Materials Which Are Aerosols
RESP	Fractions of Aerosols Which Are Respirable
PSPROB	Pasquill Atmospheric Stability Class Weights
CIPKG	Curies per Package by Isotope
FRGAMA, FRNEUT [1]	Fractions of Radiation Which Are Gamma & Neutron
Isotope Definition	Cloudshine Factor
Constants [2]	Inhalation Effective Dose Equivalent
	Ingestion Effective Dose Equivalent
	Food Transfer Factor
	Soil Transfer Factor
	Deposition Velocity
	Lung Type Designation
LDIST	Link Length
LPOPD	Link Population Density
LARAT	Link Accident Rate
RADIST [1]	Radii of Non-dispersal Accident Exposure Annuli
BRATE	Breathing Rate
BDF	Fraction of Respirable Aerosol Inside Buildings
RPD	Ratio of Pedestrian Density to Population Density
RU [1]	Urban Building Shielding Factor
CULVL [3]	Cleanup Level

1 Non-dispersal accidents only
2 Taken from published sources; not suitable for statistical variation
3 Adjustable but there are no guidelines for valid range

Table II. Results of Sensitivity Tests: Changes in Total Accident-Risk for Changes in Selected Variables Yielding Non-Proportional Sensitivity

Variable	Reference Value Input	Test Input	Reference Result	Test Result
BRATE	3.3E-4	1.6E-4	2.72E-08	2.72E-08
BDF	8.6E-3	8.6E-4	2.72E-08	2.72E-08
		8.6E-2	2.72E-08	2.73E-08
RPD	6.0	3.0	2.72E-08	2.70E-08
		12.0	2.72E-08	2.78E-08
RU	0.018	0.01	2.97E-11	2.96E-11
		0.18	2.97E-11	3.08E-11
CULVL	0.20	0.10	2.72E-08	2.58E-08
		0.02	2.72E-08	2.21E-08

Table III. RADTRAN Accident Risk Input Variables, Sensitivity and Disposition

RADTRAN Variable	Sensitivity	Suitable for LHS?
SEVFRC	Proportional	Yes
RFRAC	Proportional	Yes
AERSOL*	Proportional	No
RESP*	Prop., Inhal. & Resusp.	No
PSPROB	Significant to Dispersal	Yes
CIPKG**	Proportional	No
FRGAMA, FRNEUT**		No
Isotope Definition Constants	Generally not subject to adjustment	No
LDIST**	Proportional	No
LPOPD	Proportional	Yes
LARAT	Proportional	Yes
RADIST**	Negligible	No
BRATE	Negligible	No
BDF	Negligible	No
RPD**	Negligible	No
RU	Negligible	No
CULVL	Small	No

* These variables describe ranges of behavior rather than point estimates.

** These variables are not generally subject to random uncertainties.

Table IV. Results (person-rem) of LHS Analysis

Input Variable	Total Accident Risk (Avg.)	Standard Deviation (50 Obs's.)	Comments
(1) PSPROB	2.57E-05	4.14E-06	6 Independent Samples for each Observation
(2) LPOPD (±10%)	5.31E-05	2.48E-06	σ of normal distribution is ±10% of mean
(3) LPOPD (±25%)	5.30E-05	6.18E-06	σ of normal distribution is ±25% of mean
(1) & (2)	2.56E-05	4.23E-06	Samples from both dist's. used in each RADTRAN calculation
(1) & (3)	2.56E-05	5.00E-06	Samples from both dist's. used in each RADTRAN calculation