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UNCERTAINTY IN TRANSPORTATION RISK ASSESSMENT

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ABSTRACT

Transportation risk assessment involves a number of parameters whose values are uncertain. RADTRAN[®] (hereinafter referred to simply as RADTRAN) is now capable of handling uncertain input parameters. Most input parameters in transportation risk assessments are uncertain, so that single-valued parameters can result in an inaccurate representation of risk. Incorporating uncertainty increases the accuracy and precision of the analysis. This paper presents the method of introducing uncertainty and the results of using different distributions for the following RADTRAN inputs: size of exposed populations, particle deposition velocities, fractions of material released from a cask under various accident conditions, fractions of released material that is aerosolized, radionuclide inventory of spent nuclear fuel (since burnup and age may be uncertain), and meteorological parameters.

INTRODUCTION

RADTRAN (Neuhauser *et al.* 2000) is a computer code capable of performing probabilistic risk assessment for the transportation of radioactive materials. RADTRAN is able to interface with Sandia's Latin Hypercube Sampling (LHS) program (Wyss and Jorgensen 1998) to assign probability density functions (PDF) to selected RADTRAN input variables. However, LHS tends to over-emphasize the tails of the PDF, meaning that low-probability events are equally sampled with high-probability events. Monte Carlo Sampling (MCS) is a practical alternative, which uses a random number generator to sample a PDF. As a result, MCS yields more sample values near the peak of the PDF and fewer sample values on the tails of the PDF.

RADTRAN requires that a majority of input parameter values be user-defined; therefore, the user needs a certain familiarity with appropriate values. A number of RADTRAN input parameters were selected for distribution in the MCS system; however, the input parameters and output sample sets selected for MCS are different from those in LHS. Fifteen input variables were selected for distribution because they vary widely depending on such factors as geography, atmospheric conditions, time of day, transportation cask type, and spent nuclear fuel burnup and cooling time. Figure 1 outlines the input and output parameters chosen for distribution.

Distributed Inputs	Package Dose Rate	Stop Time	Vehicle Dose Rate	Stop Population Density	Urban Vehicle Speed	Rural Shielding Factor	Suburban Shielding Factor	Urban Shielding Factor
	Curie Loading	Wind Speed	Release Height	Deposition Velocity	Suburban Vehicle Speed	Evacuation Time	Building Dose Factor	
Distributed Outputs	Crew Exposure	On-Link Exposure	Off-Link Exposure	Individual In-Transit Dose	Stop Exposure	Handling Exposure	Groundshine	
	Inhalation	Cloudshine	Ruspension	Total	Red Marrow	Thyroid	Effective	

Figure 1. Distributed RADTRAN Input and Output Parameters

A Sandia-developed graphical user interface for MCS (Gauntt and Erickson 2004) has been obtained and approved for implementation in RADTRAN. With this software, the user is able to view the default probability density and cumulative distribution functions (CDF) of each distributed RADTRAN input parameter. The RADTRAN Uncertainty Analysis Module visualizes the sampled points as red dots while also allowing the user to change the range and shape of the default distribution, type of distribution, and the number of points sampled.

DEFAULT DISTRIBUTIONS

A default PDF is assigned to each of the input parameters selected for distribution (Dennis, Penisten and Weiner 2004). All default distributions are beta distributions, but with different A , B , p , and q values, which characterize the shape of the distribution. The distribution occurs over a range from A to B , and is shaped by p and q . Constraints are that p and q must both be greater than or equal to 0.001 and $0 \leq A < B$.

The beta distribution was selected as the default for all parameters because it is a flexible distribution. It can represent uniform, triangular, Poisson, log-normal, Gaussian, and other PDFs simply by varying p and q . The effects of varying p and q in the beta distribution are shown in Figure 2.

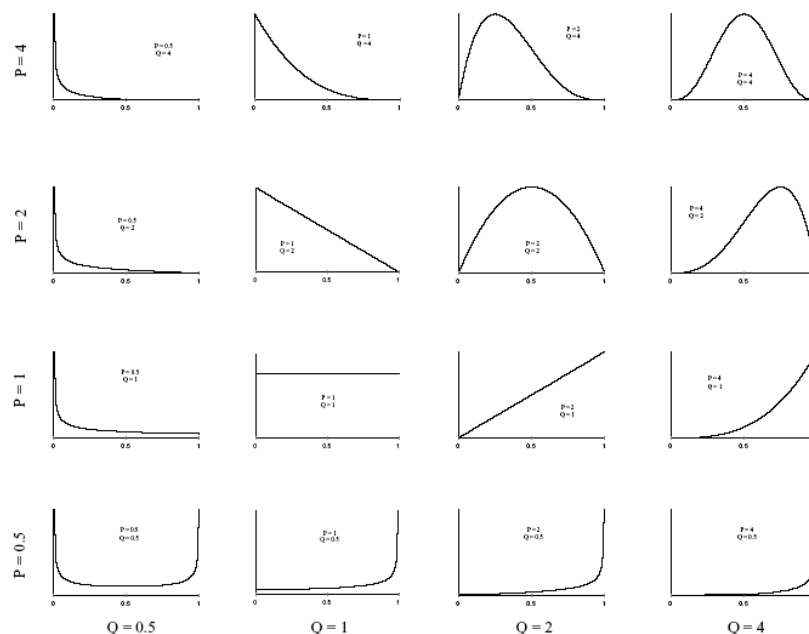


Figure 2. Beta Distribution for Varying p and q (Wyss and Jorgensen 1998)

The PDF, $f_X(x)$ for the beta distribution is defined as (Papoulis and Pillai 2002):

$$f_X(x) = \frac{x^{p-1} \cdot (1-x)^{q-1}}{\int_A^B x^{p-1} \cdot (1-x)^{q-1} dx} \quad \text{Equation 1}$$

The distribution has a mean of $p/(p+q)$ and a variance of $pq/((p+q)^2(p+q+1))$.

Curie Loading Distribution

The curie load will vary depending on the type of radioactive material being transported. Thus, default probability distributions are created for eighteen radionuclides in spent fuel. The eighteen radionuclides were selected based on their fissile and weapons-usable potential, as well as their large contribution to activity in a geological repository.

The default distributions for the eighteen radionuclides are based on ORIGEN calculations for PWR spent nuclear fuel with 3.81% initial U-235 enrichment, an average burnup of 40,000 MWD/MTHM, and a 5-year cooling period. The characteristic parameters of the default beta distributions are shown in Table 1.

Table 1. Parameters for Default Curie Content Distributions for Select Radionuclides

Radionuclide	p	q	A	B
Co-60	20	8.2	127	3278
Ni-63	16	9.5	0	320
Sr-90	20	9	12126	46523
Tc-99	20	9	1.59	7.5
I-129	18	11	0	0.03
Cs-134	14.5	12	0	34755
Cs-137	27.5	13	2503	73811
U-234	1	6	0.118	0.6
U-235	25	15	0.978	1
U-238	100	100	0.849	0.861
Np-237	25	16.8	0	0.39
Pu-238	9.5	12	0	4638
Pu-239	26	11	84	220
Pu-240	25	14	0	427
Am-241	22	4.5	0	705
Am-243	8.2	11	0	32
Cm-243	8.5	11	0	31
Cm-244	4	8	0	6372

Of course, the user may add or subtract nuclides as they choose, along with altering the default distribution based on the number of transported assemblies, cooling time, initial enrichment or burnup. For instance, a lower initial enrichment or burnup will shift the PDF toward the left, while higher initial enrichment or burnup will shift the PDF toward the right.

Wind Speed Distribution

A distribution of wind speeds is obtained from Table J-21 in Volume II of the Yucca Mountain Environmental Impact Statement (US DOE 2002). Six average wind speeds (m/s) are tabulated with the associated probabilities for each stability class. The wind speed probabilities for stability class B serve as the default wind speed distribution in the RADTRAN Uncertainty Analysis Engine. The characteristic parameters of all stability classes' wind speed distributions are given in Table 2.

Table 2. Parameters for Default Wind Speed Distributions

Stability Class	p	q	A	B
A	1	1.7	0	5
B	1	1.4	0	7
C	2.7	4	0	13
D	3	3.3	0	13
E	2.1	4	0	13
F	1.02	1.4	0	5
G	1	2	0	3

Other Distributions

Characteristic parameters of the remaining 13 input beta distributions are shown in Table 3.

Table 3. Parameters for Remaining Default Beta Distributions

Variable	p	q	A	B
Package Dose Rate (mrem/hr)	4	4	0	10
Vehicle Dose Rate (mrem/hr)	4	4	0	10
Vehicle Speed – Urban (m/s)	3.9	3.9	30	96
Vehicle Speed – Rural (m/s)	4	3.4	30	96
Stop Time (hr)	2	4.5	0	1
Persons at the Stop	6.8	6.8	0	12.8
Shielding Factor – Urban	2	4	0	1
Shielding Factor – Suburban	4	4	0	1
Shielding Factor – Rural	4	2	0	1
Deposition Velocity (m/s)	4.1	8.9	0	0.008505
Building Dose Factor	1	1	0	1
Fire-Only Release Height (m)	1	1.5	71	101
Evacuation Time (hr)	2	6	0	24

UNCERTAINTY ENGINE LOGIC

The RADTRAN Uncertainty Analysis Module requires a certain familiarity with RADTRAN input text files. While the user can manipulate text file uncertainty distributions using the MELCOR Uncertainty Engine Graphical User Interface (GUI), major alterations to distributed variables must be made using the RADTRAN text file and a text editor. The following outline grossly chronicles how to implement the module. For more detailed instructions, please refer to Dennis et al. 2007.

- A RADTRAN input file is created that identifies single values for appropriate parameters.
- Default PDFs or user-defined PDFs are chosen for each uncertain input parameter.
- The number of samples is chosen between 5 and 500.
- Each distributed parameter is randomly sampled at one point on its distribution.

- The combination of randomly sampled points for each distributed parameter constitutes a single RADTRAN input file.
- A batch file executes RADTRAN for each input file and creates an output that corresponds to each input.
- The batch file combines output values in bins of similar results, producing an output PDF.

It is important to define distributed parameters, initialize the type of distribution and set bounds at the beginning of an input text file. Figure 3 illustrates the necessary logic located before the *TITLE* variable in a typical RADTRAN input.

```

*%DEF%CURIE1=Co60 curie content (Ci)
*%DEF%CURIE10=U238 curie content (Ci)
*%DEF%CURIE11=Np237 curie content (Ci)
*%DEF%DEP1=Particulate deposition velocity (m/s)
*%DEF%DEP2=Cesium deposition velocity (m/s)
*%DEF%DEP3=Ruthenium deposition velocity (m/s)
*%DEF%DEP4=CRUD Deposition velocity (m/s)
*%DEF%EVACUATION=Evacuation time for groundshine (days)
*%DEF%STOP2=Suburban stop time (hr)
*%SIZE%NSAMPLE=5
*%INIT%CURIE1=BETA,20,8.2,6600,170448
*%INIT%CURIE10=BETA,100,100,16.08,16.8
*%INIT%CURIE11=BETA,25,16.8,0,24
*%INIT%DEP1=BETA,4.1,8.9,0,0.008505
*%INIT%DEP2=BETA,4.1,8.9,0,0.008505
*%INIT%DEP3=BETA,4.1,8.9,0,0.008505
*%INIT%DEP4=BETA,4.1,8.9,0,0.008505
*%INIT%EVACUATION=BETA,2,8,1,36
*%INIT%STOP2=BETA,4.5,2,2,24

```

Figure 3. Uncertainty Initialization Logic

It is equally important to place the defined variables in Figure 3 in the appropriate location. For instance, a deposition velocity would have a singular value. However, when distributing this value, the singular deposition velocity value is replaced with the definition “%#DEP1#%”. Figure 4 exemplifies how this appears in the input file.

```

RELEASE
GROUP=PARTS
RFRAC
0.00E+00 1.37E-07 2.52E-07 1.32E-05 1.37E-05 1.43E-05
AERSOL
1.00E+00 1.00E+00 1.00E+00 1.00E+00 1.00E+00 1.00E+00
RESP
1.00E-01 1.00E-01 1.00E-01 1.00E-01 1.00E-01 1.00E-01
DEPVEL %#DEP1#%
PACKAGE SFUEL 14.0 1.000 0.000 5.20
CO60 %#CURIE1#% CRUD

```

Figure 4. Uncertainty Variable Emplacement Logic

APPLICATION

Incorporating uncertainty in RADTRAN risk assessments improves the realism of RADTRAN analyses by reflecting, in the output, uncertainty in input parameter values. The example discussed in this section, a spent nuclear fuel (SNF) rail shipment from Nine Mile Point nuclear power plant to Caliente, NV, illustrates how the front-end of the RADTRAN Uncertainty Analysis Module functions. Again, the user should have significant familiarity with RADTRAN input files as well as having read the module user guide (Dennis, Weiner, et al. 2007). For this example, Table 4 outlines the distributed parameters, units, and upper and lower bounds. These values essentially represent 24 SNF assemblies, 3 year cooled, and transported in a steel-lead-steel rail cask.

Table 4. Distributed Input Parameters as Beta Distributions

Distributed Input Parameter	Units	Minimum	Maximum
CO60	Curies	6600	170448
U238	Curies	16.08	16.8
Np237	Curies	0	24
Pu238	Curies	0	241128
Pu239	Curies	4368	11472
Pu240	Curies	0	22320
Am241	Curies	0	37248
Am243	Curies	0	1704
Cm243	Curies	0	1776
Cm244	Curies	0	331440
Ni63	Curies	0	16680
Sr90	Curies	629520	2420904
Tc99	Curies	81.6	508.8
I129	Curies	0	1.44
Cs134	Curies	0	18077704
Cs137	Curies	130200	3840000
U234	Curies	0	6.48
U235	Curies	22.8	24
Particulate Dep. Velocity	m/s	0	0.008505
Cesium Dep. Velocity	m/s	0	0.008505
Ruthenium Dep. Velocity	m/s	0	0.008505
CRUD Dep. Velocity	m/s	0	0.008505
Evacuation Time	days	1	36
Urban Stop Time	hours	2	24

Any RADTRAN input parameters not listed in Table 4 above are singular values in the input file. Once the input file is created, the Uncertainty Analysis Engine randomly samples points on the user-defined distribution. Figure 5 is an example of how the urban stop time CDF and PDF appear after or during manipulation of the type of distribution (beta, normal, log-normal, etc.) and the number of sample points.

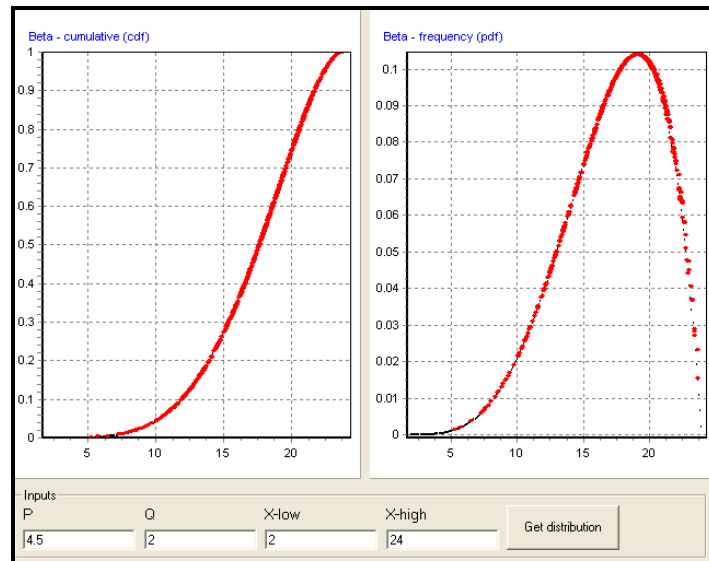


Figure 5. Urban Stop Time Beta Distribution CDF and PDF

RESULTS

Once all distributions are verified, the module writes each case file, representing in this case 500 separate RADTRAN input files. Each input file now has a randomly sampled number in place of the definitions illustrated previously in Figure 4. Finally, RADTRAN is called in batch mode and the significant output parameters listed in Figure 1 are culled from each RADTRAN output file and finally assembled in an Excel spreadsheet.

From the rail cask example, we will discuss only one of the fourteen possible output distributions. Since curie content and deposition velocity were distributed inputs, it is prudent to look at one of the accident outputs, namely total expected population risk. Figure 6 is a histogram of total risk in person-rem.

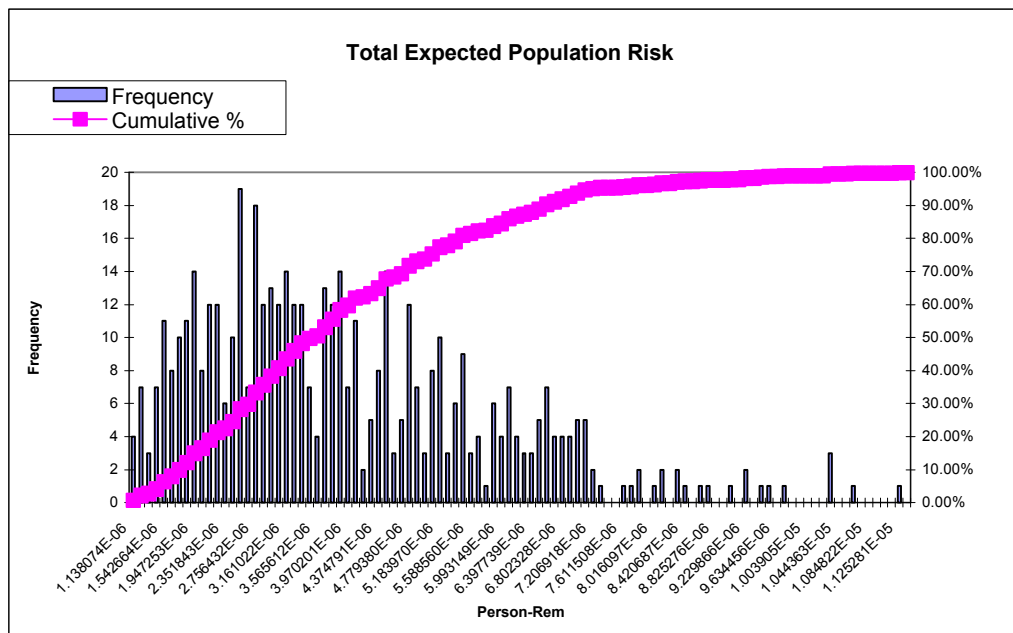


Figure 6. Histogram of Total Expected Population Risk [person-rem]

The PDF shape in Figure 6 can be attributed to the trend of both the input deposition velocity and evacuation time distributions. Given that the population risk is influenced by how much material settles out in an accident, the similar trend is expected.

CONCLUSIONS

The RADTRAN Uncertainty Analysis Module provides an entirely new capability for radioactive materials transportation risk assessment. By no longer requiring each input be a singular value, the module expands RADTRAN's realism and gives the user more flexibility in defining parameters which in reality may extend over a range of probable values. Future iterations of the module will most likely incorporate the RadCat GUI, a treatment for coupled parameters, and allow for user selection of various output parameters other than those currently hard-wired.

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