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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 with Monte Carlo sampling. Many 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. Monte Carlo Sampling (MCS) is a practical method of sampling and uses a random number generator to sample an input parameter distribution.

Almost all input parameter values in RADTRAN can be user-defined; therefore, the user needs a certain familiarity with the appropriate values. A number of RADTRAN input parameters were selected for distribution in the MCS system. 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 | Vehicle Speed | Rural Sheilding Factor | Suburban Shielding Factor | Urban Shielding Factor |
|---|---|---|---|---|---|---|---|---|
| | Curie Loading | Wind Speed | Release Height | Deposition Velocity | Release Fraction | 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 | Resuspension | 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) is implemented in RADTRAN. With this software, the user is able to view the default probability distribution and cumulative distribution functions (CDF) of each distributed RADTRAN input parameter as in Figure 2. 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 probability distribution function (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.

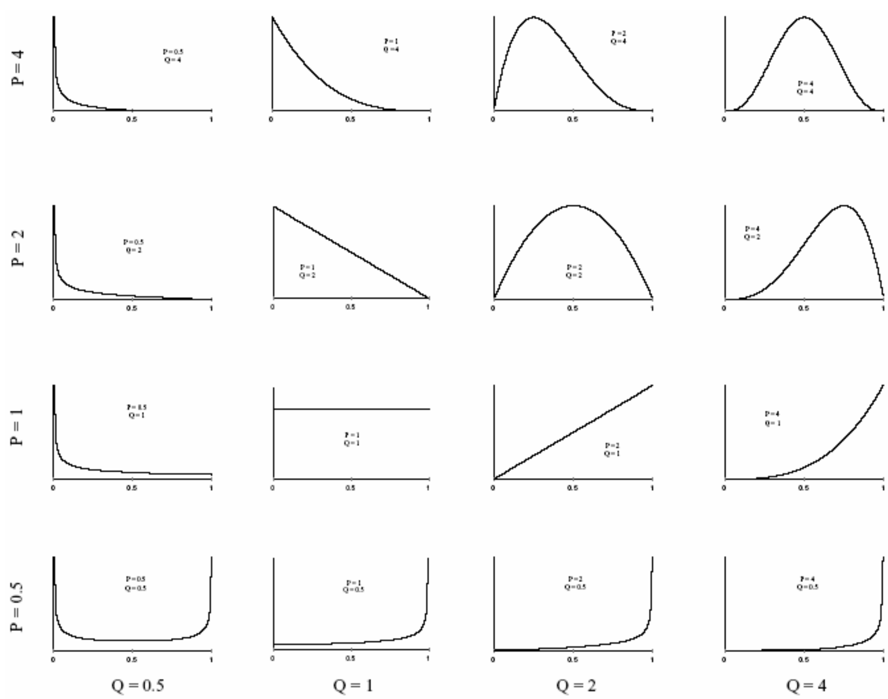


**Figure 2: Beta Distribution for Varying p and q (Wyss and Jorgensen 1998)**

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

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

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

Radioactivity Loading Distribution

The radioactivity load will vary depending on the type of radioactive material being transported. Thus, default probability distributions are created for eighteen radionuclides in spent fuel. These eighteen radionuclides were selected based on 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 Radioactivity Distributions**

| 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 he or she chooses, 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 distribution toward the left, while higher initial enrichment or burnup will shift the distribution 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 familiarity with RADTRAN input text files. While the user can manipulate the text file uncertainty distributions using the MELCOR Uncertainty Engine Graphical User Interface (GUI), major alterations in which variables are distributed 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 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 and initialize the type of distribution and bounds at the beginning of an input text file. Figure 3 illustrates the necessary logic located before the *TITLE* variable in 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. 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 |

RADTRAN input parameters not listed in Table 4 above are single-valued. 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.

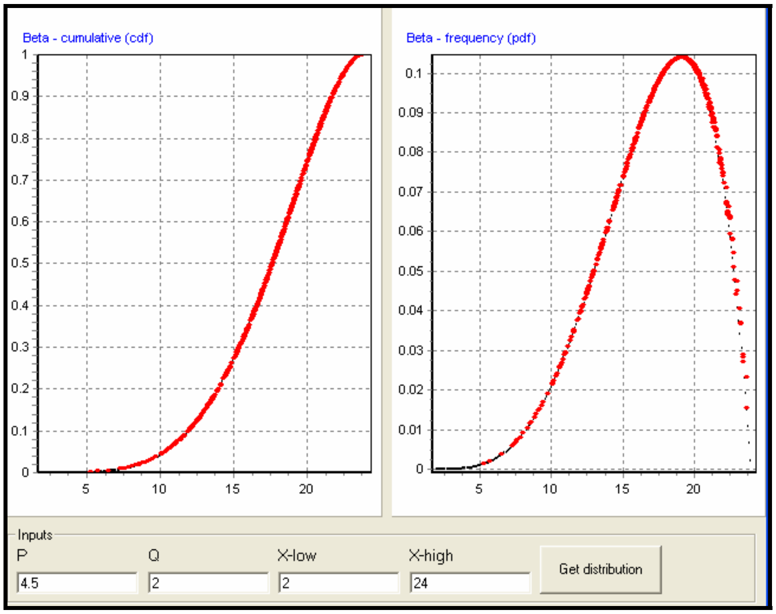


**Figure 5: Urban Stop Time Beta Distribution CDF and PDF**

## 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.

One of the fourteen possible output distributions from the rail cask example is presented here. 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.

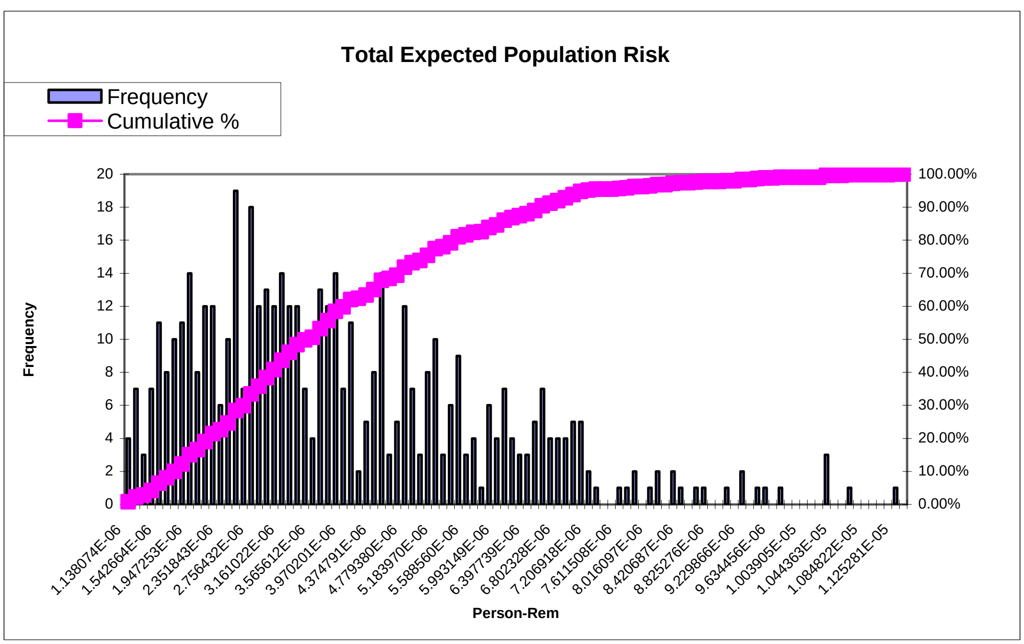


**Figure 6: Histogram of Total Expected Population Risk [person-rem]**

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 a new capability for radioactive materials transportation risk assessment. By no longer requiring each input be a singular value, the module allows more realism in RADTRAN analyses and gives the user more flexibility in defining parameter which in reality may extend over a range of probable values. Future iterations of the module will most likely incorporate the graphical user interface input file generator and a treatment for coupled parameters.

## REFERENCES


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