PNNL-32241 Rev. 3

NRC-Radioactive Material Transport (RADTRAN) Tasks 1-3

March 2023

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Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Contract DE-AC05-76RL01830
Interagency Agreement: 31310019N0001
Task Order Number: 31310021F0024

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

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Acronyms and Abbreviations

AEC	U.S. Atomic Energy Commission
AVD	adjacent vehicle distance
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EA	environmental assessment
EIS	environmental impact statement
ERI	Energy Research, Inc.
GUI	graphical user interface
LOS	loss-of-shielding
m	meters
MEI	maximally exposed individual
mrem/hr	milli Roentgen equivalent man per hour
NAC-LWT	Nuclear Assurance Corporation-Legal Weight Truck
NRC	U.S. Nuclear Regulatory Commission
NRC-RADTRAN	U.S. Nuclear Regulatory Commission-Radioactive Material Transport
PNNL	Pacific Northwest National Laboratory
RAMP	Radiation Protection Computer Code Analysis and Maintenance Program

Contents

Figures

Tables

1.0 Introduction

The U.S. Nuclear Regulatory Commission-Radioactive Material Transport (NRC-RADTRAN)[1] computer code is used to estimate radiation doses and risks to populations and workers (crew members) resulting from incident-free transportation of radioactive material and doses and risks to the populations from transportation accidents. For the analysis of incident-free transportation doses, radiation doses are estimated for individuals who would share transportation routes with shipments—called on-link populations, individuals who live along the route of travel—called off-link populations, and individuals exposed at stops. For accident risks, RADTRAN estimates radiation doses and risks from accidents involving the dispersal of radioactive material, and accidents involving the loss of radiation shielding. The NRC assigned Pacific Northwest National Laboratory (PNNL) with three tasks involving RADTRAN:

1. Task 1. Compare the source codes between NRC-RADTRAN 6.02.1 (current version in Radiation Protection Computer Code Analysis and Maintenance Program [RAMP][2]) and RADTRAN 6.1 to determine any coding differences, input requirements, and output changes. In addition, determine if any action is necessary to finish development of RADTRAN 6.1, including verification and validation, and to ensure functionality with the NRC-RADTRAN graphical user interface (GUI).
2. Task 2. Compare NRC-RADTRAN output with spreadsheet calculations based on appropriate technical methodologies (e.g., RADTRAN 6 Technical Manual, NUREGs, etc.).
3. Task 3. Determine what information or documentation may be necessary to maintain, modify, and/or update the NRC-RADTRAN v1.0 GUI source code such that it is compatible with any future updates to the RADTRAN analytical code and any future operating system upgrades.

This paper describes the results of performing Tasks 1 through 3.

[1] Except where the distinction between NRC-RADTRAN and other versions of RADTRAN is important, the NRC-RADTRAN code is referred to as RADTRAN.
[2] RAMP is the NRC's Radiation Protection Computer Code Analysis and Maintenance Program.

2.0 Task 1 Objective and Results

The objective of Task 1 was to compare differences such as input requirements, output format, and coding changes between RADTRAN versions 6.02.1 and 6.1. A file comparison was performed between the Energy Research, Inc. (ERI) RADTRAN 6.02.1 source code and the RADTRAN 6.1 source code and is provided as a file named "radtran6021_619.fc.pdf". There are numerous differences between the two versions of the source code. It appears that most changes eliminate compiler error and warning messages and do not affect the functionality of the codes. The types of changes addressing compiler errors and warning messages have been discussed in Zavisca et al. (2019).

Differences in the source code that change the functionality of the code affect the loss-of-shielding (LOS) model that is implemented by the two versions of RADTRAN. The RADTRAN 6.02.1 LOS model is based on the model described in SAND2009-5107, Dose Estimates in a Loss of Lead Shielding Truck Accident (Dennis et al. 2009). Dennis et al. (2009) is not cited in the RADTRAN 6 Technical Manual (Weiner et al. 2014) and the description of the LOS model in the RADTRAN 6 Technical Manual is not of sufficient detail to enable verification and validation to be performed without also referring to Dennis et al. (2009) and the RADTRAN source code. In addition, RADTRAN 6.1 made several changes to the LOS model from Dennis et al. (2009):

1. The value for the parameter B_COEF0 was changed from 2.40 in RADTRAN 6.02.1 to 5.76 in RADTRAN 6.1. No documentation of this change was noted in the RADTRAN 6.1 source code.
2. The pre-defined distances at which LOS accident consequences are calculated were changed (Table 1). No documentation of this change was noted in the RADTRAN 6.1 source code.
3. In estimating the dose at 2 meters (m) from a LOS accident, RADTRAN 6.02.1 uses Equation 5 in Dennis et al. (2009) for slump fractions that are ≤ 10% and uses Equation 6 for slump fractions > 10%. RADTRAN 6.1 uses Equation 5 for slump fractions that are ≤ 15% and Equation 6 for slump fractions > 15%. It should be noted that there is an inconsistency between RADTRAN 6.02.1 and Dennis et al. (2009), wherein RADTRAN 6.02.1 uses Equation 5 for slump fractions ≤ 10% while Dennis et al. (2009) uses Equation 5 for slump fractions < 10%.
4. RADTRAN 6.02.1 calculates LOS doses at fixed distances that are either specified by the user or pre-defined (Table 1) and does not calculate LOS doses based on annular areas. The user is allowed to enter the data required to estimate annular doses; however, annular doses are not estimated. RADTRAN 6.1 appears to have added an annular LOS model; however, no documentation associated with this change was provided in the RADTRAN 6.1 source code and without documentation the functionality of this annular LOS model could not be evaluated.

Table 1. RADTRAN Pre-Defined Loss-of-Shielding Distances

RADTRAN 6.02.1 Distance (m)	RADTRAN 6.1 Distance (m)
1	1
2	2
3	4

RADTRAN 6.02.1 Distance (m)	RADTRAN 6.1 Distance (m)
4	9
5	20
10	40
20	60
50	80
100	100
Maximum	Maximum

In terms of the functionality of the RADTRAN GUI, it should be noted that the current version of the GUI cannot be used to develop an air cargo or passenger air RADTRAN calculation. A work-around solution is to develop the air transport run as a truck run, save the input file, manually edit the input file with a text editor to change the transport mode to 5 (air cargo) or 6 (passenger air), re-import the input file into the GUI and run it, and RADTRAN will execute correctly, and the GUI does not fail.

A review of the input and output files was conducted for identical runs using version 6.02.1 and version 6.1. The input and output files were imported to Microsoft Word documents in order to use the file compare functionality in Microsoft Word. Using the file compare system, the version 6.02.1 file was listed as the revision and the version 6.1 file was listed as the original document. All input files were verified to be identical for a series of seven runs that used varying inputs.

There were a series of expected differences between the output files. These are related to output identification for revisions and also the headers and footers that present information unique to each run. In addition to the expected differences, the output files of all seven comparisons contained differences. Certain differences were identified as organizational (i.e., reordering of Input Data in the input echo) while others may have been more significant. In every run a stop sensitivity analysis was included. The output files from 6.1 included rearrangement of tables and exclusion of accidents with conditional probabilities of zero. No calculational differences were identified during the output comparison.

Changes in outputs between the two versions may be attributed to the implementation of the annular dose LOS model in version 6.1. Documentation was not readily available for the annular LOS model. In addition, references to changes to the LOS model described by Dennis et al. (2009) were not readily available.

3.0 Task 2 Objective and Results

Excel spreadsheet calculations were performed for comparing with the RADTRAN 6.02.1 results in case of incident-free and accident scenarios for the truck, rail, barge, and air transport modes. The ExceLab add-in version 7.0 (available at https://excel-works.com/) was used to solve the equations that require numerical integration. For the incident-free scenarios (i.e., doses to crew members, on-link doses, off-link doses, doses at fixed distance stops, and doses at annular stops), gamma and neutron scenarios were evaluated separately. Since several RADTRAN calculations depend on transportation overpackage sizes, two transportation package sizes were evaluated, the Nuclear Assurance Corporation-Legal Weight Truck (NAC-LWT) (length of 5.1 m and diameter of 1.1 m) (NRC Docket No. 71-9225) and the 9975 (length of 0.90 m and diameter of 0.47 m) (NRC Docket No. 71-9975). Calculations for the following variables or scenarios were performed in this effort:

1. Incident-free gamma and neutron exposure scenarios for truck, regular and dedicated rail, and barge. These scenarios are typically used in NRC environmental impact statements (EISs) for new reactors, EISs for consolidated interim storage facilities, and U.S. Department of Energy (DOE) environmental assessments (EAs) and EISs.
2. Accident scenarios involving the dispersal of radioactive material. These scenarios are also typically used in NRC EISs for new reactors, EISs for consolidated interim storage facilities, and DOE EAs.
3. Accidents involving LOS. These types of accidents are not typically analyzed but may become more important as EAs and EISs for transport of spent nuclear fuel transition from shipping bare fuel in transportation casks to shipping fuel in canisters in transportation casks (e.g., NRC 2014).
4. Air cargo and passenger air incident-free gamma and neutron exposure scenarios. Based on literature review, very few of these types of analyses were performed in the United States.

3.1 Incident-Free Gamma Results

The incident-free gamma scenarios in RADTRAN do not account for attenuation by air or buildup, the resulting equations are based on analytical solutions to point kernel or point kernel integral equations. Besides the maximally exposed individual (MEI) in-transit gamma doses, the RADTRAN incident-free gamma results were in close agreement with spreadsheet calculations with less than 1 percent difference. However, obtaining this agreement would not have been possible based on the equations in the RADTRAN 6 Technical Manual alone, and at times the RADTRAN 3 (Madsen et al. 1986), RADTRAN 4 (Neuhauser and Kanipe 1993), and RADTRAN 5 (Neuhauser et al. 2000) manuals were used, and WASH-1238 (AEC 1972) was referred to for an integral derivation. In addition, access to the RADTRAN source code was critical because there were cases where the RADTRAN 6 Technical Manual did not reflect what was being implemented in the RADTRAN source code.

The MEI in-transit gamma dose calculation is not discussed in the RADTRAN 6 Technical Manual and discussion of the calculation last appeared in the RADTRAN 4 Technical Manual (Neuhauser and Kanipe 1993). In contrast to the other incident-free gamma calculations, the MEI in-transit gamma dose calculation accounts for attenuation by air and buildup and must be solved numerically. In RADTRAN, this is done by approximating the point kernel integral equation as a zero order Bessel function using the subroutine BESSL. PNNL attempted to duplicate the MEI in-transit dose calculation through numerical integration of the point kernel equation using the Excel add-in ExceLab (Equation 1):

$$\int_x^\infty \frac{\exp(-\mu \times r) \times B(r)}{r\sqrt{r^2 - x^2}}\, dr = \int_x^\infty \frac{\exp(-\mu \times r) \times \left(1 + 0.006r\right)}{r\sqrt{r^2 - x^2}}\, dr \left(units\ of\ m^{-1}\right) \quad \text{Equation 1}$$

An approximate difference of about -10% was observed between the RADTRAN result and the spreadsheet calculation (i.e., the ExceLab calculation was about 10 percent lower than the RADTRAN calculation). PNNL also simplified the calculation using an analytical solution that does not include attenuation by air or buildup, as used in the other incident-free gamma scenarios and obtained results about 14 percent higher than the RADTRAN calculation. Neither the ExceLab approach nor the analytical solution approach yielded a matching result.

3.2 Incident-Free Neutron Results

The equations used in RADTRAN to estimate incident-free neutron doses account for attenuation by air, buildup and consequently must be evaluated using a combination of analytical methods and numerical methods (Table 2). In cases where an analytical solution was used to estimate the incident-free neutron dose, extremely close agreement was obtained, typically less than 1 percent difference (Table 2). This was also the case when a numerical solution involving a single integral was used to estimate the incident-free neutron dose. For cases where a double integral was used to estimate the incident-free neutron doses for example, off-link doses (Equation 2), the percent difference was found to be much higher (Table 3).

$$\int_{min}^{max} \left[\int_x^\infty \frac{\exp(-\mu \times r) \times \left(1 + a_1 \times r + a_2 \times r^2 + a_3 \times r^3 + a_4 \times r^4\right)}{r\sqrt{r^2 - x^2}}\, dr \right] (no\ units) \quad \text{Equation 2}$$

For truck mode of transportation, the difference for off-link doses ranged from 1 to 86 percent. A difference of about 86 percent was estimated for off-link doses using rail transportation. For barge transport, the differences for the off-link doses were greater than 500 percent. The differences observed between the spreadsheet-calculated and RADTRAN-calculated off-link doses also increase with exposure distance (Figure 1), where the difference observed for a 5 m minimum exposure distance was approximately 42 percent while the percent difference observed for a 500 m minimum exposure distance was about 3200 percent.

Table 2. Solution Method Used for RADTRAN Incident-Free Neutron Doses

Scenario	Method	Percent Difference (%)
Crew Dose	Analytical	< 1
Fixed distance stop	Analytical	< 1
Annular stop	Numerical (single integral)	< 1

Scenario	Method	Percent Difference (%)
Rail classification doses	Analytical	< 1
On-Link doses	Numerical (single integral)	1 - 40
Off-Link doses (Excluding Barge)	Numerical (double integral)	1 - 86

Table 3. Incident-Free Off-Link Neutron Dose Percent Differences

Segment Type	Segment Character	Percent Difference for NAC-LWT Transportation Package (%)	Percent Difference for 9975 Transportation Package (%)
Freeway	Rural	85	86
Freeway	Suburban	86	85
Freeway	Urban	86	86
Non-Freeway	Rural	64	64
Non-Freeway	Suburban	61	61
Non-Freeway	Urban	1.1	1.2
City Streets	Rural	64	64
City Streets	Suburban	61	61
City Streets	Urban	1.1	1.2
Rail	Rural	85	86
Rail	Suburban	86	86
Rail	Urban	85	86
Barge	Rural	> 500	> 500
Barge	Suburban	> 500	> 500
Barge	Urban	> 500	> 500

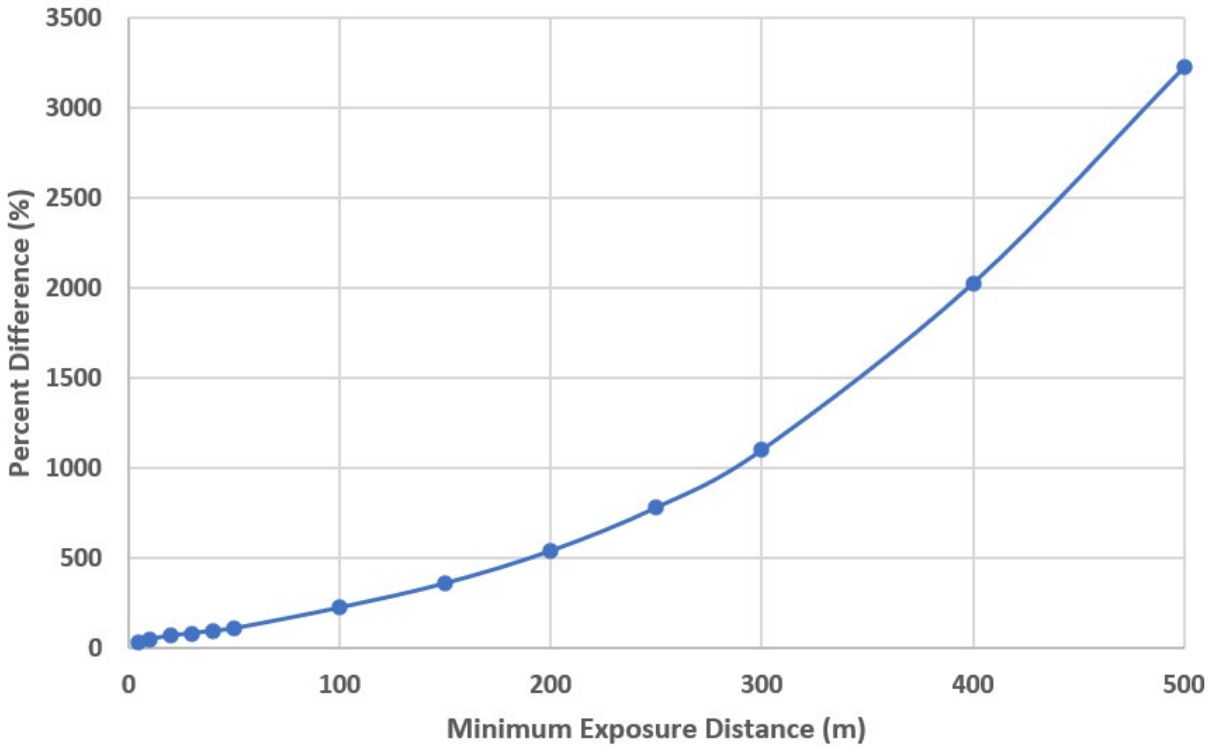

Figure 1. Percent Differences Between Spreadsheet-Calculated and RADTRAN-Calculated Neutron Off-link Doses as a Function of Minimum Exposure Distance

For the MEI in-transit neutron dose, RADTRAN uses the same equation and data used for MEI in-transit gamma dose, even though air has different attenuation and buildup properties for gamma and neutron radiation. For the passenger air calculations, the passenger dose and the flight attendant dose for gamma and neutron doses also use the same data and equations.

An additional issue concerns the on-link incident-free neutron dose calculations, wherein doses are estimated for individuals passing a shipment. According to the RADTRAN manuals, in those cases Equation 3 was used:

$$\text{Passing in Same Direction On-Link Dose (person-rem)} = \frac{2\times k(0)(\text{point source})(m^2)\times DR\left(\frac{mrem}{hr}\right)}{(Speed^2)\left(\frac{m^2}{s^2}\right)} \times \text{Distance}(km) \times \frac{Persons}{Vehicle} \times \frac{Vehicles}{hr} \times \left(\frac{rem}{1000\ \text{mrem}}\right) \times \left(\frac{1000\ m}{km}\right) \times \left(\frac{hr}{3600\ s}\right)^2 \times Integration\ Value \qquad \text{Equation 3}$$

Where,

$$Integration\ Value = \frac{1}{2} \times \int_{AVD}^{\infty} \frac{exp(-\mu \times r) \times (1 + a_1 \times r + a_2 \times r^2 + a_3 \times r^3 + a_4 \times r^4)}{r^2} dr - \frac{1}{2} \times \int_{MED}^{\infty} \frac{exp(-\mu\times r)\times(1+a_1\times r+a_2\times r^2+a_3\times r^3+a_4\times r^4)}{r^2} dr \ \ (units\ of\ m^{-1}) \qquad \text{Equation 4}$$

$$\text{Minimum Exposure Distance (MED)}\ (m) = Speed\left(\frac{km}{hr}\right) \times \frac{1000\ m}{km} \times \frac{hr}{3600\ s} \times 2\ s \qquad \text{Equation 5}$$

In Equation 4, AVD is the adjacent vehicle distance and MED is the minimum exposure distance (Equation 5). While investigating the source code, it was discovered that Equation 6 was implemented.

$$\text{Passing in Same Direction On-Link Dose (person-rem)} = \frac{2 \times k(0)(\text{point source})(m^2) \times DR\left(\frac{mrem}{hr}\right)}{(Speed^2)\left(\frac{m^2}{s^2}\right)} \times \text{Distance}(km) \times \frac{Persons}{Vehicle} \times \frac{Vehicles}{hr} \times \left(\frac{rem}{1000\text{ mrem}}\right) \times \left(\frac{1000\ m}{km}\right) \times \left(\frac{hr}{3600\ s}\right)^2 \times Integration\ Value \qquad \text{Equation 6}$$

Where,

$$Integration\ Value = \frac{1}{2} \times \left(\int_{AVD}^{\infty} \frac{dr}{r^2} - \int_{MED}^{\infty} \frac{exp(-\mu \times r) \times (1 + a_1 \times r + a_2 \times r^2 + a_3 \times r^3 + a_4 \times r^4)}{r^2} dr\right)$$

$$= \frac{1}{2} \times \left(\frac{1}{AVD} - \int_{MED}^{\infty} \frac{exp(-\mu \times r) \times (1 + a_1 \times r + a_2 \times r^2 + a_3 \times r^3 + a_4 \times r^4)}{r^2} dr\right)\ (units\ of\ m^{-1}) \qquad \text{Equation 7}$$

$$\text{Minimum Exposure Distance (MED)}(m) = Speed\left(\frac{km}{hr}\right) \times \frac{1000\ m}{km} \times \frac{hr}{3600\ s} \times 2\ s \qquad \text{Equation 8}$$

The difference between Equation 3 and Equation 6 is in terms of the integration value (Equation 4 and Equation 7). Instead of using the neutron integral for the AVD integral, RADTRAN uses the analytical solution to the gamma integral, (i.e., AVD^{-1}).

3.3 Regulatory Checks

The RADTRAN code has the ability to perform regulatory checks to verify that radiation dose rates meet the U.S. Department of Transportation (DOT) regulatory requirements. Typically, the dose rate limit at 2 m from the edge of the vehicle (10 milli Roentgen equivalent man per hour [mrem/hr]) provides the most stringent regulatory check, i.e., if the 10 mrem/hr limit is met then the other dose rate limits are met (49 CFR 173.441(a)). To determine whether the regulatory check in RADTRAN functions correctly, PNNL performed truck and rail RADTRAN runs with vehicle dose rates that would exceed the 10 mrem/hr limit and observed that RADTRAN reduced the vehicle dose rates to meet the 10 mem/hr limit. It should be noted that RADTRAN does not incorporate an offset between the transportation package and the edge of the vehicle, i.e., the transportation package is assumed to be at the edge of the vehicle.

PNNL also performed RADTRAN runs to verify that the driver dose rate limit (2 mrem/hr) was implemented by RADTRAN. It should be noted that this limit does not apply to drivers who are radiation workers. Also, RADTRAN does not perform the 2 mrem/hr check for rail crew members because the crew was not assumed to be in a security escort railcar.

3.4 Accidents Involving Dispersal of Radioactive Material

Spreadsheet calculations were performed to verify and validate the accident dispersal calculations performed by RADTRAN. Two radionuclides were evaluated, krypton-85 (Kr-85) and cesium-137 (Cs-137). The Kr-85 was evaluated because it provides an example of an inert, non-depositing gas that contributes radiation dose exclusively through the immersion pathway. The Cs-137 was evaluated because it provides an example of a radionuclide that contributes radiation dose through the inhalation, resuspension, immersion, and groundshine pathways.

Extremely close (within 0.1%) agreement was observed between the spreadsheet of calculated results and the RADTRAN-calculated results. However, the following items were noted:

1. For the inhalation, resuspension, and immersion pathways, RADTRAN calculates doses using the geometric mean of the depleted atmospheric dilution factors (χ/Qs) (Table 4). While for the groundshine pathway, RADTRAN calculates doses using the depleted χ/Qs, instead of the geometric mean of the depleted χ/Qs. There is no technical explanation for this switch however, it is likely that using the depleted χ/Qs would yield lower radiation doses compared to that using the geometric mean of the depleted χ/Qs.
2. Equations 65 and 66 in the RADTRAN 6 Technical Manual provide equations used to estimate resuspension doses. However, the RADTRAN source code uses equations by Penisten and Weiner (2005) and Anspaugh et al. (2002).
3. As mentioned above, RADTRAN uses the geometric mean of the depleted χ/Qs. In calculating this quantity, RADTRAN ignores the innermost isopleth.

Spreadsheet calculations for individual dose estimates (based on the RADTRAN 6 Manual equation 63) were beyond the scope of the report and were not evaluated in this work.

Table 4. Inhalation, Resuspension, Immersion, and Groundshine Pathway Percent Differences

Radionuclide	Percent Difference Inhalation Pathway (%)	Percent Difference Resuspension Pathway (%)	Percent Difference Immersion Pathway (%)	Percent Difference Groundshine Pathway (%)
Krypton-85	Not applicable (N/A)	N/A	0	N/A
Cesium-137	-0.1	0	0	0.1

3.5 Accidents Involving Loss-of-Shielding

PNNL was able to duplicate the LOS doses using spreadsheet calculations but as mentioned previously, this would not have been possible without Dennis et al. (2009) and access to the RADTRAN source code. In addition, Dennis et al. (2009) contains specific restrictions on the use of the LOS model:

1. The LOS model was based on modeling simulations performed for a generic 5.21 m long steel-lead-steel spent nuclear fuel truck transportation cask, and Dennis et al. (2009) stated that the model should only be applied to truck transportation casks. However, no such restriction or warning is implemented in the RADTRAN 6 Technical Manual, source code, or GUI, and it is possible to estimate LOS doses for large rail transportation casks.
2. The LOS model includes a fixed distance exposure model but not an annular exposure model.
3. The LOS model was developed for gamma radiation exposures and does not consider neutron radiation exposures. However, the RADTRAN source code and GUI allows neutron doses to be estimated using the LOS model with no restriction or warning.

4.0 Task 3 Objective and Results

The objective of Task 3 was to identify information necessary to maintain and modify the NRC-RADTRAN v1.0 GUI to enable future updates. PNNL noted two issues associated with the functionality associated with the GUI:

1. *RADTRAN GUI Default Parameters Screen.* The values for the default parameters used by RADTRAN are not actually listed on this screen, instead a “-1” value was used to denote that a default value was used. This is a significant limitation in the functionality of the GUI for users who need to change the values of default parameters.
2. The RADTRAN GUI Calculations and Documentation folders are not installed in directories that are normally backed up by products such as Microsoft OneDrive. This creates a potential vulnerability that users should be warned of while installing RADTRAN.

5.0 Conclusion

This section summarizes the results of the tasks assigned by the NRC to PNNL involving the RADTRAN code. Comparison of outputs from two versions (6.02.1 and 6.1) led to the determination that the implementation of the LOS model between the two versions was different. With regards to the input files, no differences were observed between the input files being used in both the versions for a wide variety of input scenarios. In the output files, however, it was observed there were organizational differences such as input echo, rearrangement of tables, and exclusion of accidents with zero probability. This was followed by performing independent hand calculations to validate the results from RADTRAN. Upon comparing the incident free gamma dose results, an absolute difference between 10 and 14 percent was observed. These calculations used an Excel add-in in conjunction with the analytical solution (that excluded attenuation by air or buildup) for comparison to the results from RADTRAN. Except for on-link and off-link doses, the incident free neutron dose for most scenarios resulted in a deviation under 1%. It was noted that the regulatory checks in RADTRAN were performed as expected. A percentage difference of under 0.1% was observed for the dispersal of radioactive material (in an accident scenario). Accidents involving the LOS model were successfully verified by accessing the source code as well as previously published literature. On the RADTRAN GUI, challenges related to the display of default parameters as well as data backup were identified by the PNNL team.

6.0 References

49 CFR 173. Title 49 of the Code of Federal Regulations Part 49. Transportation, “Shippers – General Requirements for Shipments and Packaging.” United States Department of Transportation, Washington, D.C.

AEC (U.S. Atomic Energy Commission). 1972. Environmental Survey of Transportation of Radioactive Materials To and From Nuclear Power Plants. Report No. WASH-1238.

Anspaugh LR, SL Simon, KI Gordeev, IA Likhtarev, RM Maxwell, and SM Shinkarev. 2002. Movement of Radionuclides in Terrestrial Ecosystems by Physical Processes. Health Physics Vol. 82 No. 5, pp. 669-769.

Dennis ML, RF Weiner, DM Osborn, and TJ Heames. 2009. Dose Estimates in a Loss of Lead Shielding Truck Accident. Report No. SAND2009-5107. Sandia National Laboratories, Albuquerque, NM.

Madsen MM, JM Taylor, RM Ostmeyer, and PC Reardon. 1986. RADTRAN III. Report No. SAND84-0036. Sandia National Laboratories, Albuquerque, NM.

Neuhauser KS and FL Kanipe. 1993. RADTRAN 4, Volume II, Technical Manual. Report No. SAND89-2370. Sandia National Laboratories, Albuquerque, NM.

Neuhauser KS, FL Kanipe, and RF Weiner. 2000. RADTRAN 5 Technical Manual. Report No. SAND2000-1256. Sandia National Laboratories, Albuquerque, NM.

NRC (U.S. Nuclear Regulatory Commission). 2014. Spent Fuel Transportation Risk Assessment. Report No. NUREG-2125. U.S. Nuclear Regulatory Commission, Washington, DC.

Penisten JJ and RF Weiner. 2005. Improved Resuspension Dose Model for RADTRAN Transportation Risk Assessment Code. Transactions of the American Nuclear Society, Vol. 93, No. 1, pp. 155-156.

Weiner RF, KS Neuhauser, TK Heames, BM O’Donnell, and ML Dennis. 2014. RADTRAN 6 Technical Manual. Report No. SAND2013-0780. Sandia National Laboratories, Albuquerque, NM.

Zavisca M, E Ball, and M Khatib-Rahbar. 2019. Deliverables for Subtask 2 (Review Current RADTRAN to Establish Baseline Performance) of Task Order 17 (Packaging RADTRAN and a Graphical User Interface as a U.S. Nuclear Regulatory Commission Maintained Integrated Code Package), Contract No. NRC-HQ-25-14-E-0005. Letter to D Palmrose (NRC) from M Zavisca, E Ball, and M Khatib-Rahbar (Energy Research, Inc.), ERI/NRC 2019-10-25, October 25, 2019.

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