NUREG/CR-6604
Supplement 2

RADTRAD: A Simplified Model for RADionuclide Transport And Removal And Dose Estimation

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ABSTRACT

This report provides an update to the documentation for the RADTRAD computer program developed for the U.S. Nuclear Regulatory Commission to estimate dose at selected receptors due to accidental releases of radionuclides from a nuclear facility. This report is the second supplement to the original RADTRAD documentation published as NUREG/CR-6604. Supplement 1 of the RADTRAD Users Manual was published as NUREG/CR-6604, Supplement 1. This supplement is specific to Version 3.03 of RADTRAD. Included in this report are installation instructions, a summary of code revisions, and a comparison of results from Version 3.03 to results previously published in Supplement 1 of NUREG/CR-6604.

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1.0 Introduction

The RADionuclide Transport, Removal, And Dose (RADTRAD) code is used to estimate the dose due to a postulated nuclear power plant accident at various locations outside of the containment. The current version of RADTRAD is Version 3.03. This code version corrects various errors identified by the user community in Version 3.02a.

This document is a second supplement to NUREG/CR-6604. This report summarizes changes made to Version 3.02a that have resulted in Version 3.03 and the tests performed on Version 3.03.

The report is organized into four sections including Section 1. Section 2 is a user's guide that describes the RADTRAD 3.03 installation process. Section 3 discusses the changes that were made to the code. Finally, Section 4 discusses the tests that were performed on Version 3.03 of RADTRAD.

2.0 RADTRAD User's Guide

Instructions for the installation of RADTRAD Version 3.03 and running the suite of test problems provided with the distribution are included in this section. No changes have been made to the RADTRAD program that affects use of the graphical user interface (GUI). As a result, the discussion presented in Section 1.2 of NUREG/CR-6604, Supplement 1 is still current in Version 3.03. Appendix A provides replacement pages for NUREG/CR-6604 to better describe models for containment sprays, natural deposition in containment, and deposition in piping. Changes are marked with a revision bar in the right-hand margin. Only the affected pages from NUREG/CR-6604 are included.

2.1 Installation

RADTRAD 3.03 is supplied on CD-ROM. Both the GUI and batch mode versions of RADTRAD 3.03 are provided. RADTRAD Version 3.03 runs under the various implementations of the Microsoft Windows operating system including Windows 95/98, Windows NT 4.0, Windows ME, Windows 2000 and Windows XP. Installation requires about 20 MB of disk space and a CD-ROM reader. RADTRAD Version 3.03 works best with a 17-inch or larger monitor set to a minimum resolution of 1024x768 pixels.

The distribution files for RADTRAD Version 3.03 are organized into the following directories:

1. Batch Mode Version - located in the "Batch Mode Executable" directory on the CD-ROM. Input for the sample problems are located in the "input" subdirectory. Default data files are located in the "Defaults" directory.

2. GUI Mode Version - a self-extraction installation file named "radtrad303_setup.exe" containing the GUI mode version of RADTRAD along with the data files needed to execute cases. Running this file will install the version of RADTRAD that has the graphical user interface for input preparation and code execution.

3. Documentation - contains documentation on the RADTRAD code.

4. Test Cases - contains the input and output for the installation test cases for testing purposes.

The batch version of RADTRAD can be installed by simply copying the file and directories in the "Batch Mode Executable" directory on the CDROM to a suitable directory on the hard drive of the host computer. The GUI version of RADTRAD is installed by double-clicking on the self-extracting installation file named "Radtrad3.03_setup.exe" and following the instructions for installation.

2.2 Contents of the RADTRAD Installation Directory

After installing the GUI version of RADTRAD, a main installation folder will be generated. The default name of this folder is "C:\Program Files\Radtrad3.03". Note that the location may be changed during installation. The contents of the installation directory are listed below:

1. Graphics folder - contains graphical files used to execute the GUI version of RADTRAD3.03. These bitmaps are used to display graphical icons in the GUI and cannot be moved or deleted.

2. Defaults folder - contains default data files used to run cases. Three types of files are provided: 1) the radionuclide inventory file (.nif extension), the release fraction and timing file (.rft extension), and the dose conversion factors file (.inp extension).

3. Input folder - contains the set of input files for installation checking. It is suggested that a copy of this folder be placed in a working subdirectory for use. The execution files for RADTRAD (vbradrad.exe and radtrad.dll) are also included.

To start the GUI version of RADTRAD, click on Start->Programs. Then, click on the RADTRAD 3.03 icon. Instructions for running the GUI version of RADTRAD have not changed since Supplement 1 of NUREG/CR-6604 was published. The steps are as follows:

- Start RADTRAD by clicking on Start->Programs->Radtrad3.03. On the RADTRAD splash screen, click on the "Begin" button.

- Click on File->Open RADTRAD Input or equivalently click on the "open file" icon on the toolbar. Then navigate to the input file directory.

- Choose an input file from the PSF files displayed (Test1.psf, Test10.psf, etc.). After the file is read, the name of the selected file and a derived unique filename for RADTRAD output are displayed in the status bars at the bottom of the main RADTRAD window.

- Make input changes as necessary. When complete, save the input by clicking on File->Save Radtrad Input or click on the "save file" icon on the toolbar.

- Click on the "Calculate" button to initiate a Radtrad calculation with the current input file. When the calculation is complete, a navigable text window will open displaying the results.

Details on the GUI interface are presented in Section 1.2 of NUREG/CR-6604, Supplement 1.

For the batch mode version, the installation directory can be organized to suit the user's needs. The only item to note is that the defaults directory needs to be in the same location as the executable file to run cases. The path to the location of the executable location can be set to allow access to the code from any directory on the hard drive. For Windows 98, NT-4.0 and ME systems, the path can be set in the "autoexec.bat" file. The steps for setting the path in Windows XP are listed in Table 1.

The command line for execution, given the availability of a suitable input file in the directory where the RADTRAD executable file is located or a correctly set path to the executable is:

radtrad /b input_file_name output_file_name

3.0 Differences Between RADTRAD 3.03 and RADTRAD 3.02a

A number of changes were made to both the GUI Visual Basic code and the RADTRAD analysis code which is written in Fortran. Changes were made to GUI code to make it more user friendly and to correct some errors that were identified by various users. The GUI was modified to allow the user to more easily delete compartments, pathways, or dose locations. In addition, changes were made to allow the user to select a pathway transport model and get default (no decontamination) values and to allow the user to see the valid input range for the Power's spray model. Also, the maximum number of dose locations was fixed at 5. A brief summary of changes made to each routine is presented in Table 2.

Some fundamental modeling corrections were made that are summarized below:

1) If the control room airflow is large (> 1000 cfm), the radionuclide exhausted from the control room reentered the environment in Version 3.02a, thus increasing the radionuclide concentration in the environment and the offsite dose results. If this exhaust rate were sufficiently high, the control room dose would also be unrealistically increased because of the higher radionuclide concentration. This problem was corrected in Version 3.03 by removing the radionuclides exhausted from the control room from the calculation.

2) If there is more than one pathway to the environment from a single compartment, the radionuclide intake into the control room was computed incorrectly in Version 3.02a. As an example, if there were three pathways, the control room radionuclide intake from these pathways was counted three times. This problem was corrected in Version 3.03.

3) If there is a suppression pool pathway, any noble gases injected into the pool were retained in the pool volume in Version 3.02a. In addition, the exit volume and the inflow volume were assumed to be the same resulting in the exhaust flow being incorrectly calculated. Treatment of noble gases was corrected in Version 3.03.

4) If a very high pathway flowrate to a volume was specified (> 25%/minute), it was possible to totally exhaust a compartment of radionuclides in Version 3.02. In fact, it was possible to create negative radionuclide quantities if the exhaust rate was high enough. These quantities were balanced with the creation of extra radionuclides in the system thus increasing the dose. Calculation of radionuclide quantities in high flow rate situations was corrected in Version 3.03.

In addition RADTRAD V3.03 added input checking to prevent the use of correlations outside their range of applicability. Additional information was added to the output such as mass balance results, comparisons of decontamination results among volumes, and additional input summaries to allow input verification. These changes result in increased user input flexibility.

4.0 RADTRAD 3.03 Test Cases

Tables 3 to 5 compare the results generated from RADTRAD 3.03 to the results previously published in NUREG/CR-6604, Supplement 1. The results are found to be in agreement. Note that there is a change to the tests listed. The four release cases for the analytic solution tests listed in Table 4.5 of NUREG/CR-6604, Supplement 1 (Cases 6 and 7) were deleted from the test suite because they are no longer applicable to the principal purpose of RADTRAD, which is to analyze design basis accidents.

5.0 References

1. Humphreys, S.L., T.J. Heames, L.A. Miller, and D.K. Monroe, RADTRAD: A Simplified Model for RADionuclide Transport, and Removal And Dose Estimation, NUREG/CR-6604, Sandia National Laboratories, Albuquerque, N.M., 1998

2. Bixler, N.E. and C.M. Erickson, RADTRAD: A Simplified Model for RADionuclide Transport, and Removal And Dose Estimation, NUREG/CR-6604, Supplement 1, Sandia National Laboratories, Albuquerque, N.M., 1999

Table 1
Steps to Set a Path Variable in Windows XP

1. Before starting, have the full path name of your executable file available (example: c:\radtrad3.03\radtrad.dll).

2. Click on Start, then click on My Computer.

3. Click on the "View System Information" link under the "System Tasks" Panel at the left side of the screen. This will bring up the "System Properties" dialog box.

4. Click on the "Advanced" tab.

5. Click on the "Environment Variables" button.

6. Under the "System Variables" section of this panel, scroll down until you find a row labeled "PATH". Click once on this row to highlight it.

7. Once the "PATH" row is highlighted, click the "Edit" button. This brings up the "Edit System Variable" dialog box.

8. The second text box in this dialog will be titled "Variable value". Initially, all of the text in the text box will be highlighted in blue. Click once on the text to unselect it, as you do not want to overwrite the text in this box, but simply add to it.

9. Scroll to the end of the text and add a semicolon (;) followed by the path name to your executable file that you noted earlier.

10. Press the OK button to exit the "Edit System Variable" dialog box.

11. Press the OK button to exit the "Environment Variables" dialog box.

12. Press the OK button to exit the "System Properties" dialog box.

13. You may need to restart your computer in order for the path changes to take effect.

To Check If Your Executable's Path Is Included in Your System's Path:

1. Click on Start, then go to All Programs, then go to Accessories.

2. Under Accessories, click on Command Prompt.

3. In the command prompt that pops up, type path. Windows will report to you what it's path variable is currently set to. You should see your file listed somewhere in this report. If not, and you followed all the steps listed above, try restarting your computer.

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
FORTRAN Source Files						
aerosol	x	x	x	N	Y	Corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.
apwrdba	x	x	x	N	Y	Corrected an error in the coefficient in the natural deposition model for APWR. Also corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.
aqueous	x	x	x	N	Y	An external definition to a routine called DZPORC, which is an IMSL math library routine, was deactivated. In version 3.03, the definition was left in and the IMSL library was linked during compilation. It is noted that the coding in aerosol is not used in either Version 3.02a or 3.03, but may be used in the future.
ash	x	x	x	N	Y	Reset a minimum to 10^{-20} to allow 0 flow in the environment.
autodt	x	x	x	N	N	N/A
bixler1	x	x	x	N	N	N/A
bixler3	x	x	x	N	N	N/A
brock	x	x	x	N	Y	Corrected an error in a coefficient for the Gormley & Kennedy turbulent deposition model. Fixed output error for situation where intercompartmental flow becomes 0.0.

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
bwrdba	x	x	x	N	Y	Corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.
bwrsa	x	x	x	N	Y	Corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.
cin	x	x	x	N	N	N/A
coeffs	x	x	x	N	Y	Changed the code so that the offsite dose remains unchanged if a control room is included in the problem. In previous code versions, unfiltered radionuclides discharged from the control room exhaust were reintroduced into the environment affecting the dose results.
cout	x	x	x	N	N	N/A
dkngro	x	x	x	N	Y	Code modification made to recalculate the sum of the radionuclide group inventory after decay and daughter calculations are complete.
doses	x	x	x	N	N	N/A
energyc	x	x	x	N	N	N/A
energyp	x	x	x	N	N	N/A
filtin	x	x	x	N	N	N/A
fout	x	x	x	N	N	N/A

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
hscommon			x	N/A	N/A	N/A
init_err			x	N/A	N/A	N/A
initall	x	x	x	N	N	N/A
jac	x	x	x	N	N	N/A
lupc1	x	x	x	N	N	N/A
lupc2	x	x	x	N	N	N/A
lupl2	x	x	x	N	N	N/A
lupp1	x	x	x	N	N	N/A
lupp2	x	x	x	N	N	N/A
masstr	x	x	x	N	N	N/A
necsteps	x	x	x	N	N	N/A
nextunit	x	x	x	N	N	N/A
nifout	x	x	x	N	N	N/A
opool	x	x	x	N	N	N/A
parse_cl	x (batch version only)	x (batch version only)	x (batch version only)	N	N	N/A
pipin	x	x	x	N	Y	Coding corrected so that the correct effective decontamination factors are written for the piping and Brockman models.
pipout	x	x	x	N	N	N/A
pmfout	x	x	x	N	Y	Increased dose conversion factor filename length to avoid unintended code termination.
printhdr	x	x	x	Y	Y	Increased dose conversion factor filename length to avoid unintended code termination.

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
printout	x	x	x	N	Y	Following changes to the code output made: 1) Coding corrected so that the correct effective decontamination factors are written for the piping and Brockman models, 2) Output the release fraction, release timing file, and the nuclide inventories specified in the respective default data files (.nif, .rft, etc.), 3) Output the dose conversion factor data for the whole body, thyroid, and effective inhalation, 4) Output compartment type information, 5) Output corrected group transport values when daughtering selected, and 6) Output the EAB 2 hour dose. Finally, the decontamination factor was redefined to be: $(N_{atmosphere}+N_{deposited})/N_{atmosphere}$ where N is the number of atoms. Fixed code to correctly output maximum EAB dose and location description.
printpmf	x	x	x	N	Y	Change name to pathway edits in input listing
printsdf	x	x	x	N	Y	Added information to the output that indicates whether decay or daughter production is considered in the problem.
pwrdba	x	x	x	N	Y	Corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.
pwrsa	x	x	x	N	Y	Corrected an error in the implementation of the Powers natural deposition model. Problem was that running different release modes in separate runs produced different total results than combining the identical release modes in the same run because the deposition as a function of release time was different.

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
radcalc	x	x	x	N	Y	Corrected a programming error where multiple release paths from a compartment to the environment caused the environmental dose to be incorrectly computed. Problem was that the dose results for a single release path to the environment at a given flow rate and radionuclide concentration were different than the results computed for two release paths, each at half the flow rate but with the same nuclide concentration as the single pathway case. Affected the environmental dose only. Corrected a programming error where the control room filter loading calculation used an incorrect array. Filter loading values for control room filters were incorrect. The dose results were not affected. Corrected a programming error where the radionuclide concentration in volumes downstream of a suppression pool volume was computed incorrectly.
radtrad	x (batch version only)	x (batch version only)	x (batch version only)	N	N	N/A
radtradl	x (dll library only)	x (dll library only)	x (dll library only)	N	Y	Removed leading blanks from the output file name specification.
rd_nif	x	x	x	N	Y	Added array to save initial radionuclide inventory for mass balance checking.

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
rd_pmf	x	x	x	N	Y	Increased dose conversion factor filename length to avoid unintended code termination.
rd_psf	x (batch version only)	x (batch version only)	x (batch version only)	N	N	N/A
rd_rft	x	x	x	N	Y	Corrected a programming error in the release fraction and timing (.rft) file where time = 0 specified in the release timing for a particular release category is intended to mean that no release in that category occurs.
rd_sdf	x	x	x	N	Y	Initialization of mass quantities changed to double precision. Initialized array counters and miscellaneous terms.
rdflag	x	x	x	N	N	N/A
rdinpd	x	x	x	N	Y	File name check (between version 3.01 and 3.02 and later).
recirc	x	x	x	N	N	N/A
rftout	x	x	x	N	Y	Output release fraction data from the default release fraction data file (see changes to printout routine).
rhs	x	x	x	N	N	N/A
sorter	x	x	x	N	N	N/A
source	x	x	x	N	Y	Synchronized pathway mass arrays so that mass data is consistent with respect to time.
spinit	x	x	x	N	N	N/A
spry	x	x	x	N	N	N/A
sterm	x	x	x	N	N	N/A
supin	x	x	x	N	Y	Modified code so that noble gas will be transported through the suppression pool volume (similar to non-reactive organic iodine)
supout	x	x	x	N	Y	Modified code so that noble gas will be transported through the suppression pool volume (similar to non-reactive organic iodine)

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
limits	x	x	x	N	N	N/A
names	x	x	x	N	N	N/A
nat_dep	x	x	x	N	N	N/A
necstcmp	x	x	x	N	N	N/A
necstloc	x	x	x	N	N	N/A
necstpth	x	x	x	N	N	N/A
necstrel	x	x	x	N	N	N/A
necstspr	x	x	x	N	N	N/A
necstsrt	x	x	x	N	N	N/A
nif	x	x	x	N	Y	Save initial nuclide mass in common block.
op	x	x	x	N	N	N/A
opvol	x	x	x	N	N	N/A
p_filter	x	x	x	N	N	N/A
pathway	x	x	x	N	Y	
piping	x	x	x	N	N	N/A
ptran	x	x	x	N	Y	Added total transport through the path as well as deposition in the path to the full output edit to allow the user to determine the worst dose path. Limited extrapolated mean mass in a compartment to a positive value (issue when rapidly changing conditions in a compartment cause wide variations in the mean compartment mass).
rel_time	x	x	x	N	N	N/A
simulate	x	x	x	N	N	N/A
source	x	x	x	N	N	N/A
sp	x	x	x	N	N	N/A
sp_vol	x	x	x	N	N	N/A
spool	x	x	x	N	N	N/A

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
sprays	x	x	x	N	N	N/A
sump	x	x	x	N	N	N/A
sump_vol	x	x	x	N	N	N/A
water	x	x	x	N	N	N/A
Visual Basic Code						
frmAbout.frm	x	x	x	N	N	N/A
frmBrockman.frm	x	x	x	N	Y	Added input checking to the Brockman model.
frmCalcOptions.frm	x	x	x	N	N	N/A
frmCompartment.frm	x	x	x	N	Y	Several fixes to the compartment input interface to allow easier editing and deleting of data.
frmData.frm	x	x	x	N	Y	Modified interface to allow specification of suppression pool flows by radionuclide type (noble gases ,elemental iodine, etc.)
frmDoseLocation.frm	x	x	x	N	Y	Several fixes to the dose location input interface to allow easier editing and deleting of data. Fixed a delay time error.
frmHelp.frm	x	x	x	N	N	N/A
frmHenry.frm	x	x	x	N	N	N/A
frmITSmodification.frm	x	x	x	Y	Y	Revised modification details for Version 3.03.
frmMain.frm	x	x	x	Y	N	N/A
frmPathways.frm	x	x	x	N	Y	Several fixes to the pathways input interface to allow easier editing and deleting of data. Fixed error related to changing from compartment to compartment.
frmPowersDep.frm	x	x	x	N	Y	Added input checking to the Powers deposition model.
frmPowersPool.frm	x	x	x	N	N	N/A
frmPowersSpray.frm	x	x	x	N	Y	Added input checking to the Powers spray model.
frmProgress.frm	x	x	x	N	N	N/A

Table 2
Summary of Changes Made to the RADTRAD Code

	RADTRAD Version			Changed from 3.02 to 3.02a	Changed from 3.02a to 3.03	Description of Changes
	3.02	3.02a	3.03			
frmSourceTerm.frm	x	x	x	N	Y	Added input checking to the source term interface. Also added a check for existence of the input file.
frmSplash.frm	x	x	x	Y	N	N/A
frmStatus.frm	x	x	x	N	N	N/A
frmTxtEdit.frm	x	x	x	N	Y	Fixed a buffer problem in the post processing text editor.
Module1.bas	x	x	x	N	Y	Integrated source file that compiles changes made to Visual Basic forms through the IDE. Reset a counter to fix "Unused" error.

Table 3
Control Room and Deposition Test Comparisons

		Exclusion Area Boundary		Low Population Zone		Control Room		Control Room Activity	
Test Case	Code	Doses (rem)		Doses (rem)		Doses (rem)		(Curies)	
		Thyroid	TEDE	Thyroid	TEDE	Thyroid	TEDE		
PWR Control Room and Natural Deposition Tests									
TID-14844								^{131}I	^{135}Xe
1	RADTRAD 3.03 RADTRAD 3.01 HABIT	444 444 443	13.6 13.6 13.6	2992 2990 2990	91.9 91.9 91.9	– – --	– – --	– – --	– – --
2	RADTRAD 3.03 RADTRAD 3.01 HABIT	653 653 652	28.8 28.8 28.8	4401 4400 4400	220 220 220	– – --	– – --	– – --	– – --
3	RADTRAD 3.03 RADTRAD 3.01 HABIT	653 652 653	28.8 28.8 28.8	4401 4400 4400	220 220 220	2657 2660 2650	95.4 95.5 95.1	3.95E-3 3.95E-3 4.00E-3	0.75 0.75 --
4	RADTRAD 3.03 RADTRAD 3.01 HABIT	1134 1130 1130	47.5 47.5 47.6	808 809 808	66.8 66.9 66.8	4943 4950 4920	169 169 168	7.32E-3 7.32E-3 7.42E-3	0.75 0.75 --
5	RADTRAD 3.03 RADTRAD 3.01	1302 1300	54.1 54.1	8466 8470	392 392	5299 5300	180 180	7.87E-3 7.87E-3	0.75 0.75
NUREG-1465/PWR								^{131}I	^{135}Xe
6	RADTRAD 3.03 RADTRAD 3.01 HABIT	354 354 354	10.8 10.8 10.8	4905 4905 4905	151 151 151	– – --	– – --	– – --	– – --

Table 3
Control Room and Deposition Test Comparisons

		Exclusion Area Boundary		Low Population Zone		Control Room		Control Room Activity	
Test Case	Code	Doses (rem)		Doses (rem)		Doses (rem)		(Curies)	
		Thyroid	TEDE	Thyroid	TEDE	Thyroid	TEDE		
7	RADTRAD 3.03 RADTRAD 3.01 HABIT	518 518 518	25.3 25.3 25.3	7200 7200 7200	382 382 382	– – --	– – --	– – --	– – --
8	RADTRAD 3.03 RADTRAD 3.01 HABIT	518 518 518	25.3 25.3 25.3	7200 7200 7200	382 382 382	480 481 479	25.7 25.7 25.6	7.31E-4 7.31E-4 –	0.15 0.15 --
9	RADTRAD 3.03 RADTRAD 3.01 HABIT	477 477 477	23.4 23.4 23.4	707 707 707	54.3 54.4 54.3	179 179 178	12.7 12.7 12.6	2.52E-4 2.52E-4 –	0.15 0.15 --
10	RADTRAD 3.03 RADTRAD 3.01	504 509	24.6 24.9	856 829	61.8 60.4	186.0 184.8	13.0 12.9	2.52E-4 2.52E-4	0.15 0.15
10A	RADTRAD 3.03 RADTRAD 3.01	472 471	23.1 23.1	689 690	53.5 53.6	178 179	12.7 12.9	2.52E-4 2.52E-4	0.15 0.15
BWR–Control Room and Pipe Deposition Tests									
TID-14844		(^{131}I only)							
11	RADTRAD 3.03 RADTRAD 3.01 HABIT	6.25 6.25 6.26	0.192 0.192 0.192	2054 2050 2050	63.1 63.1 63.1	– – --	– – --	– – --	– – --
12	RADTRAD 3.03 RADTRAD 3.01 HABIT	6.25 6.25 6.25	0.192 0.192 0.192	2054 2050 2050	63.1 63.1 63.1	279 279 277	8.49 8.49 8.44	3.40E-3 3.40E-3 3.40E-3	– – --

Table 3
Control Room and Deposition Test Comparisons

		Exclusion Area Boundary		Low Population Zone		Control Room		Control Room Activity	
Test Case	Code	Doses (rem)		Doses (rem)		Doses (rem)		(Curies)	
		Thyroid	TEDE	Thyroid	TEDE	Thyroid	TEDE		
13	RADTRAD 3.03 RADTRAD 3.01 HABIT	0.284 0.284 0.277	0.0087 0.0087 0.0085	147 147 145	4.52 4.52 4.45	376 376 372	11.5 11.5 11.3	4.92E-3 4.92E-3 4.86E-3	– – --
14	RADTRAD 3.03 RADTRAD 3.01	0.119 0.119	0.004 0.004	39 39	1.20 1.20	97.5 97.5	3.0 3.0	1.19E-3 1.19E-3	– –
NUREG-1465/BWR		(^{131}I only)							
13B	RADTRAD 3.03 RADTRAD 3.01 HABIT	0.0175 0.0175 0.0151	5.35E-4 5.35E-4 4.60E-4	87.1 87.1 86.5	2.67 2.67 2.60	213 213 211	6.48 6.48 6.44	2.99E-3 2.99E-3 --	– – --
14B	RADTRAD 3.03 RADTRAD 3.01	0.0040 0.0040	1.22E-4 1.22E-4	4.59 4.59	0.141 0.141	4.66 4.66	0.142 0.142	5.72E-5 5.72E-5	– --
15	RADTRAD 3.03 RADTRAD 3.01 HABIT	3.41 3.41 3.41	0.105 0.105 0.104	82.2 82.2 82.2	2.53 2.53 2.53	– – --	– – --	– – --	– – --
16	RADTRAD 3.03 RADTRAD 3.01 HABIT	3.41 3.41 3.41	0.105 0.105 0.104	82.2 82.2 82.2	2.53 2.53 2.53	44.7 44.7 44.2	1.36 1.36 1.35	1.54E-4 1.54E-4 1.56E-4	– – --

Table 3
Control Room and Deposition Test Comparisons

		Exclusion Area Boundary		Low Population Zone		Control Room		Control Room Activity	
Test Case	Code	Doses (rem)		Doses (rem)		Doses (rem)		(Curies)	
		Thyroid	TEDE	Thyroid	TEDE	Thyroid	TEDE		
PWR–Natural Deposition and Spray Tests									
NUREG-1465/PWR								^{131}I	^{135}Xe
19	RADTRAD 3.03 RADTRAD 3.01 HABIT	314 314 315	9.62 9.62 9.66	3485 3485 3480	107 107 107	– – --	– – --	– – --	– – --
20	RADTRAD 3.03 RADTRAD 3.01 HABIT	459 459 460	22.7 22.7 22.7	5070 5070 5070	342 342 342	– – --	– – --	– – --	– – --
21	RADTRAD 3.03 RADTRAD 3.01 HABIT	459 459 460	22.7 22.7 22.7	5070 5070 5070	342 342 342	674 670 669	60.1 59.8 59.7	1.46E-3 1.44E-3 1.51E-3	0.987 0.988 --
22	RADTRAD 3.03 RADTRAD 3.01 HABIT	424 424 425	21.1 21.1 21.1	1845 1840 1840	179 179 179	438 438 436	49.9 49.9 49.7	9.42E-4 9.42E-4 9.73E-4	0.987 0.988 --
23	RADTRAD 3.03 RADTRAD 3.01 HABIT	61.7 61.7 61.7	4.16 4.16 4.16	58.1 58.1 58.1	106 106 106	14.1 14.1 14.0	36.1 36.2 36	2.83E-5 2.83E-5 2.92E-5	0.987 0.987 --
24	RADTRAD 3.03 RADTRAD 3.01	68.9 68.6	4.55 4.54	61.0 60.4(1)	106 106	14.3 14.3(2)	36.2 36.2	2.83E-5 2.83E-5	0.987 0.987
24A	RADTRAD 3.03 RADTRAD 3.01	68.9 68.6	4.55 4.54	61.0 60.4(1)	106 106	14.3 14.3(2)	36.2 36.2	2.83E-5 2.83E-5	0.987 0.987

Table 4
PWR and BWR Decay and Daughter Production Tests

		Exclusion Area Boundary		Low Population Zone		Containment Activity		
Test Case	Code	Dose (rem)		Dose (rem)		(Curies)		
		Thyroid	TEDE	Thyroid	TEDE			
TID-14844						^{131}I	^{135}Xe	^{131m}Xe
1	RADTRAD 3.03 RADTRAD 3.01 HABIT	444 444 443	13.6 13.6 13.6	2992 2990 2990	91.9 91.9 91.9	1.14E7 1.14E7 1.14E7	– – --	– – --
2	RADTRAD 3.03 RADTRAD 3.01 HABIT	653 653 652	28.8 28.8 28.8	4401 4400 4400	220 220 220	1.14E7 1.14E7 1.14E7	9.37E7 9.37E7 9.37E7	4.64E5 4.64E5 4.64E5
2A	RADTRAD 3.03 RADTRAD 3.01 HABIT	641 641 640	26.3 26.3 26.2	1626 1620 1610	53.1 53.0 52.6	8.61E5 8.61E5 8.60E5	0 0 0	8.08E4 8.08E4 8.81E4
2B	RADTRAD 3.03 RADTRAD 3.01	641 641	26.3 26.3	1617 1620	52.8 53.0	8.61E5 8.61E5	0 0	1.07E5 1.07E5[3]
NUREG-1465/PWR						^{131}I	^{135}Xe	^{137}Cs
6	RADTRAD 3.03 RADTRAD 3.01 HABIT	354 354 354	10.8 10.8 10.8	4905 4905 4905	151 151 151	1.89E7 1.89E7 --	– – --	– – --
7	RADTRAD 3.03 RADTRAD 3.01 HABIT	518 518 518	25.3 25.3 25.3	7200 7200 7200	382 382 382	1.89E7 1.89E7 --	1.88E7 1.88E7 --	– – --
7A	RADTRAD 3.03 RADTRAD 3.01 HABIT	507 506 505	23.5 23.5 23.4	2680 2680 2660	157 157 156	1.43E6 1.46E6 --	0 0 --	1.07E6 1.07E6 --

Table 4
PWR and BWR Decay and Daughter Production Tests

		Exclusion Area Boundary		Low Population Zone		Containment Activity		
Test Case	Code	Dose (rem)		Dose (rem)		(Curies)		
		Thyroid	TEDE	Thyroid	TEDE			
NUREG-1465/BWR						^{131}I	^{135}Xe	^{137}Cs
7B	RADTRAD 3.03 RADTRAD 3.01 HABIT	378 378 378	20.2 20.2 20.2	5531 5530 5530	327 327 326	1.44E7 1.44E7 0	2.40E7 2.40E7 --	1.18E6 1.18E6 --
7C	RADTRAD 3.03 RADTRAD 3.01 HABIT	370 370 369	18.8 18.8 18.7	2061 2060 2040	148 147 147	1.09E6 1.09E6 –	0 0 --	1.18E6 1.18E6 --
NUREG-1465/PWR						^{131}I	^{135}Xe	^{137}Cs
7D	RADTRAD 3.03 RADTRAD 3.01 HABIT	445 445 444	19.6 19.6 19.5	2515 2510 2500	150 150 150	1.38E6 1.38E6 1.37E6	Not Listed – 0	– – --

Table 5
Analytical Solution Tests

		Exclusion Area Boundary						Low Population Zone						Control Room	
		Thyroid Dose (rem)			TEDE Dose (rem)			Thyroid Dose (rem)			TEDE Dose (rem)			^{131}I Activity	
Case		RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD	
		3.03	3.01		3.03	3.01		3.03	3.01		3.03	3.01		3.03	3.01
1	TID ^{131}I														
	No Decay	444	444	444	13.6	13.6	13.6	2992	2990	2990	91.9	91.9	91.8	--	--
	Computed	443	--	--	13.6	--	--	2990	--	--	91.9	--	--	--	--
1a	TID ^{131}I	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	No Decay	--	--	--	--	--	--	--	--	--	--	--	--	1.190×10^{-2}	1.191×10^{-2}
	Computed	--	--	--	--	--	--	--	--	--	--	--	--	1.190×10^{-2}	1.190×10^{-2}
2	TID Full Source														
	No Decay	653	653	653	28.8	28.8	28.8	4400	4400	4400	220	220	220	–	–
	Computed	652	652	–	28.7	28.7	–	4400	4400	–	220	220	--	–	--

Table 5
Analytical Solution Tests

		Exclusion Area Boundary						Low Population Zone						Control Room	
		Thyroid Dose (rem)			TEDE Dose (rem)			Thyroid Dose (rem)			TEDE Dose (rem)			^{131}I Activity	
Case		RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD		HABIT	RADTRAD	
		3.03	3.01		3.03	3.01		3.03	3.01		3.03	3.01		3.03	3.01
6	PWR NUREG-1465														
	^{131}I														
	No Decay - 2 releases	354	354	354	10.8	10.8	10.8	4905	4905	4905	151	151	151	–	–
7	NUREG-1465														
	No Decay - 2 releases	518	518	518	25.3	25.3	25.3	7200	7200	7200	382	382	382	–	–

Note:

1. Number revised based on information from Terry Heames of ITSC who stated that the values listed in the Supplement are inaccurate. Note that Table 3.3.1.2-3 of NUREG/CR-6604 lists values of 60.4 for these cases.
2. Number revised based on information from Terry Heames of ITSC who stated that the values listed in the Supplement are inaccurate. Note that Table 3.3.1.2-3 of NUREG/CR-6604 lists values of 14.3 for these cases.
3. Number revised based on information from Terry Heames of ITSC who stated that the value listed in the Supplement are incorrect. Note that Table 3.3.1.2-4 of NUREG/CR-6604 lists a value of 1.07×10^5 for this case.

APPENDIX A

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user specifies a percentile. The "best estimate" value is associated with the 50th percentile, or median values; the lower bound is associated with the 10th percentile; and the reasonable upper bound, or largest decontamination factor, with the 90th percentile. The model was developed using values of 0.001, 0.1 and 0.25 cm^3 H_2O/ cm^2 s for the spray water flux, W, and fall heights of 500, 853, 1000, 1584, 2000, 3000, 4000, and 5000 cm. The model should not be used for spray water fluxes and fall heights outside of these ranges. The aerosol removal coefficient is dependent on the fraction of the aerosol suspended in the atmosphere, m_f, which is defined as the aerosol mass in the atmosphere of a compartment at a given time, t, divided by the total aerosol mass released into the compartment atmosphere until this time. The model includes the effect of the unsprayed portions of the containment by incorporating the assumption that the circulation in the compartment is rapid compared with the removal rate. The equation that specifies the aerosol removal coefficient, λ, at any time is:

$$\lambda(s^{-1}) = \frac{1}{3600(1+\alpha)}\left(\left(a + b\log^{10} W\right)\left\{1 - \left[\frac{m_f(t)}{0.9}\right]^c\right\} + \left(\frac{m_f(t)}{0.9}\right)^c\right)$$
$$\exp\left(A + B\ln W + C H + D W^2 H + E WH^2 + F W + G W^2 H^2\right) \quad (1)$$

The constants **A**, **B**, **C**, **D**, **E**, **F**, **G**, **a**, **b**, and **c** are defined in Table 2.2.1.1-1. The parameter α is the ratio of the compartment volume not exposed to sprays to the compartment volume exposed to sprays (unsprayed volume/sprayed volume). If the assumption that the circulation is rapid compared with the removal rate is not valid, then the user can split the compartment into two separate compartments and model the flow from the unsprayed portions to the sprayed portions as a convective flow. In this case α would be zero for the compartment containing the sprays.

This expression was originally developed for a puff release of aerosols into a system. In those cases where there is a continuing release, the size distribution will continually be renewed by the injected particulate. The model has been extended for this case by setting coefficients **A** through **G** to zero. This makes the model assume that the size distribution has not changed in time and that most of the material suspended is fresh material provided by the source. The aerosols removed by the sprays are placed in the sump.

where

$$DF(t) = \frac{\sum_{I=1}^{4} S_{I2,I}}{\sum_{I=1}^{4} S_{I2,I} / DF_I} \tag{13}$$

$$DF_I = \prod_{I=1}^{4} \exp\left[\lambda_{dep,I}(N\%, P_{th})\, t\right] \tag{14}$$

To compare with the original Powers document, the decontamination coefficient should be weighted by each chemical group release rate. RADTRAD does not maintain the necessary weighting factors, hence a single chemical release rate was used for the weighting coefficients. For both the severe accident and the design basis accident calculations, iodine was chosen because it releases in all four phases and is the most radiologically important. If a case is developed where the most important aerosol has a release rate significantly different than the iodine release rate, then some modification to the logic would be necessary.

Table 2.2.2.1-5 provides the decontamination coefficients for a design basis accident in an advanced PWR design. These values are based upon a Powers document [Po 97b] in which it was found that the CONTAIN-related calculation results were correlated with values in the table. These correlations do not vary with reactor thermal power; hence an approximation is used when the user selects a PWR design with a different power level. The approximation used assumes that the significant difference between the PWR and the advanced pressurized water reactor (APWR) design, in terms of natural deposition, is that the wall cooling enhances the phoretic deposition. Therefore the difference in decontamination coefficient at 1800 MWt represents this phoretic deposition and is then scaled by the power ratio. The final approximation used is:

$$\lambda_{dep}(AP_P_{th}) = \lambda_{dep}(PWR_P_{th}) + \left[\lambda_{dep}(AP_1800) - \lambda_{dep}(PWR_1800)\right]\frac{P_{th}}{1800} \tag{15}$$

where

$\lambda_{dep}(AP\text{-}P_{th})$ = decontamination coefficient from the APWR at the power level indicated (P_{th} = 1800 or design power)

$\lambda_{dep}(PWR_P_{th})$ = decontamination coefficient from the PWR design basis accident calculation for the power level indicated (P_{th} = 1800 or design power).

2.2.2.2 Elemental Iodine Removal

The user may specify a table for the natural deposition removal coefficient for elemental iodine as a function of time.

2.2.6.1 Brockmann Model for Aerosol Removal

The user may specify a table for the aerosol decontamination factor and a volumetric flow rate as a function of time for aerosols moving through the piping. Alternatively, the user may select the Brockmann model for deposition in pipes. The variation of the Brockmann model [Br91] used in RADTRAD only examines deposition in pipe bends and that due to settling, turbulent inertia,

and diffusion. The primary routine for the Brockmann model of aerosol deposition in pipes is implemented in the routine BROCK.

The mean particle diameter, d_p, is assumed to be 1 μ with an average particle density, ρ_p, of 1000 kg/m^3. The temperature, pressure, open volume, and other parameters as noted below are provided by the user.

Particles will settle due to gravitational force and deposit on the horizontally projecting lower surface of the flow path during transport. This turbulent flow deposition efficiency, η_g, is modeled as:

$$\begin{aligned} \eta_g &= 1 - \exp\left(-U_g A_s / \pi Q\right) \\ U_g &= \tau g \\ \tau &= slip\, d_p^2 \rho_p / 18\mu \\ slip &= 1.0 + 2.0\frac{mfp}{dp}\left(1.257 + 0.4e^{-0.55dp/mfp}\right) \end{aligned} \tag{18}$$

where:

U_g = gravitational deposition velocity (m/s)

τ = particle relaxation time (s)

Q = user-provided pipe gas flow (m^3/s)

A_s = user-provided total pipe surface area (m^2)

μ = viscosity of air, 1.93×10^{-5} Pa-s

mfp = particle mean free path (cm)

If the flow is laminar, then the deposition due to settling is calculated following Brockman (Fuchs, 1964) as

$$\eta_g = 1 - \frac{2}{\pi}\left[2\varepsilon\sqrt{1-\varepsilon^{2/3}} - \varepsilon^{1/3}\sqrt{1-\varepsilon^{2/3}} + \arcsin\sqrt{\varepsilon^{1/3}}\right] \tag{18a}$$

$$\varepsilon = 0.75Z - 0.75\frac{L}{D}\frac{U_g}{U}$$

$$Z = \frac{LU_g}{UD}$$

where

$L = A_s/\pi D$, horizontal pipe length

$D = 4*Vol/As$, pipe diameter

$U = Q/A_s$, the linear velocity

The laminar and turbulent settling efficiencies are equivalent for Reynolds Number between 500 and 2300.

If the flow is turbulent, then turbulence in the central core can propel a particle into the laminar sublayer. If the particle inertia is high, then it will penetrate the sublayer and be collected on the wall. There have been experiments on inertial deposition velocity [Li.74] and Brockmann has modeled the turbulent deposition efficiency, η_{turb}, as:

$$\eta_{turb} = 1 - \exp\left(-U_t A_s / Q\right)$$

$$U_t = 0.01988 U_{air} \Big/ \mathrm{Re}^{1/8} \qquad (19)$$

$$\mathrm{Re} = \rho_{air} U_{air} d_H / \mu$$

where:

U_t = turbulent inertial deposition velocity (m/s)

U_{air} = air velocity (m/s)

d_H = hydraulic diameter, 4 vol / A_s (m)

ρ_{air} = air density (kg/m^3)

When the flow is slower such that

$$\frac{\tau\, U_{air}}{d_H}\,\mathrm{Re}^{3/4} \;<\; 326.6 \tag{20}$$

then the turbulent deposition velocity is

$$U_t = 1.861\times 10^{-7}\left[\frac{\tau\, U_{air}}{d_H}\right]^2 U_{air}\,\mathrm{Re}^{11/8} \tag{21}$$

Small particles undergoing Brownian diffusion will diffuse from areas of high concentration to those of low concentration. Since the wall acts like a sink for these particles, there is net diffusion from the bulk to the wall. This phenomenon has been analyzed [Go 49] and the diffusional deposition efficiency is modeled as:

$$\eta_{diff} = 1 - \exp\left(-U_{diff} A_S / Q\right) \tag{22}$$

In laminar flow, this efficiency is modeled as:

$$\eta_{diff} = 2.56\zeta^{2/3} - 1.2\zeta - 0.177\zeta^{4/3} \tag{23}$$

$$\zeta = A_S D_{iff} \;/\; Q\, d_H \tag{24}$$

where

ζ = dimensionless diffusion parameter

D_{iff} = particle diffusion coefficient (m^2/s)

The particle diffusion coefficient is computed as:

$$D_{iff} = 1.38\times 10^{-16} Tg \times \frac{slip}{3\eta\mu dp} \tag{24a}$$

where

Tg = air temperature (k)

When the flow is slow or the pipe length is large such that $\zeta > 0.02$, then

$$\eta_{diff} = 0.819 \exp(-3.657\zeta) + 0.097 \exp(-22.3\zeta) + 0.032 \exp(-57\zeta)$$

In turbulent flow, the diffusional efficiency [Fr 77] is modeled as:

$$\eta_{diff} = 1 - \exp\left[-\zeta^{2/3}\, 0.0187\, \mathrm{Re}^{13/24} \left(\frac{L}{d_H} \right)^{1/3} \right] \tag{25}$$

where:

L = path length = $A_s / \pi d_H$ (m)

When the direction of gas flow is diverted in a bend, an aerosol particle may deviate from the gas flow due to its inertia and deposit on the wall. The efficiency of this process is modeled as:

$$\eta_{bend} = \frac{\tau U_{air} \varphi}{d_H} \tag{26}$$

where:

τ = particle relaxation time, equation 18

φ = the user-provided sum of the angles the flow has been diverted (radians)

When the flow is turbulent, this efficiency [Pu 87] is modeled as

$$\eta_{bend} = 1.0 - \exp \frac{(-2.823 \quad \tau \quad U_{air} \phi)}{d_H} \tag{27}$$

When the flow is laminar, this efficiency is modeled as:

$$\eta_{bend} = \left(1.0 + \left(\frac{\tau U_{air}}{0.171 d_H} \right)^{P_1} \right)^{-P_2} \tag{27a}$$

where:

$$P_1 = 0.452 \left(\frac{\tau U_{air}}{0.171 d_H} \right) + 2.242$$

$$P_2 = \frac{2\phi}{\pi}$$

Thus the total aerosol deposition efficiency is modeled as:

$$\eta_T = 1.0 - \left(1.0 - \eta_g\right)\left(1.0 - \eta_{turb}\right)\left(1.0 - \eta_{diff}\right)\left(1.0 - \eta_{bend}\right) \tag{28}$$

2.2.6.2 Bixler Model for Elemental Iodine Removal

The user may specify an elemental iodine decontamination factor and a volumetric flow rate as a function of time. Alternatively, the user may also select the Bixler model for deposition in pipes. With this model, the elemental iodine vapor is deposited with an efficiency, η_{ei}, as:

$$\eta_{ei} = 1 - \exp\left(-A_S U_{ei} / 100Q\right) \tag{29}$$

$$U_{ei} = e^{2809/T - 12.5} \tag{30}$$

where:

T = gas temperature (K)

The Bixler model for elemental iodine vapor deposition is based upon the Cline [Cl 91] correlation and is implemented in the routine BIXLER1.

2.2.6.3 Bixler Model for Organic Iodine Removal

The user may specify an organic iodine decontamination factor and a volumetric flow rate as a function of time. Alternatively, the user may also select the Bixler model for deposition in pipes. With this model the organic iodine vapor is deposited with an efficiency, η_{oi}, as:

$$\eta_{oi} = 1 - \exp\left(-A_S U_{oi} / 100Q\right) \tag{31}$$

$$U_{oi} = e^{2809/T - 19.30} \tag{32}$$

The Bixler model for organic iodine vapor deposition is based upon the Cline [Cl 91] results and is implemented in the routine BIXLER3.

2.2.7 Filters

The user may specify a flow and a table of the filter efficiencies (%) for the different transport groups and flow as a function of time. The model used for filtration assumes that the user-supplied fraction of material passing through the filter is retained. Thus, the decontamination coefficient is:

$$\lambda_{filter} = \left(\eta_{filter} \Big/ 100\right) F \tag{33}$$

where F is the volume-normalized flow rate (s^{-1}).

The material removed is retained by the filters. Noble gases are not filtered. This type of transport path is typically used for both filtered and unfiltered inflow into a compartment. For example, both the control room leakage inflow and filtered inflow use this model. The primary routines for filter phenomena are FILTIN for inlet filters and RECIRC for recirculating filters.

2.3 Consequence Analysis

The user provides the atmospheric relative concentrations (X/Q) for offsite locations, for example, the exclusion area boundary or the outer perimeter of the low population zone, and the control room. In addition, the breathing rates (BR) and the control room occupancy factors are provided by the user. No atmospheric transport modeling is performed by the code at this time. Typical values for atmospheric dilution can be calculated using the PAVAN [Ba 82] or ARCON model [Ra95]. The consequence models were implemented in routine DOSES.

2.3.1 Offsite Consequences Analysis

The dose to the hypothetical individual is calculated using the specified X/Qs and the amount of each nuclide released during the exposure period. The air immersion dose from each nuclide, *n,* in an environmental compartment is calculated as:

$$D_{c,n}^{env} = A_n \left(X/Q\right) DCF_{c,n} \tag{34}$$

where:

$D_{c,n}^{env}$ = air immersion (cloudshine) dose due to nuclide *n* in the environment compartment (Sv)

$DCF_{c,n}$ = FGR 11 and 12 air immersion (cloudshine) dose conversion factor for nuclide *n* as discussed in Section 1.4.3.3 (Sv m^3 / Bq s)

X/Q = user-provided atmospheric relative concentration (s / m^3)

A_n = released activity of nuclide *n* (Bq)

The activity is related to the number of atoms of nuclide *n* as:

$$A_n = N_n \lambda_n \tag{35}$$

where λ_n is the radiological decay constant for the nuclide as defined in equation 1.
The inhalation dose from each nuclide, *n*, is calculated as:

$$D_{i,n}^{env} = A_n \left(X/Q\right) BR\, DCF \tag{36}$$

where:

$D_{i,n}^{env}$ = inhalation dose commitment due to nuclide *n* in the environment compartment (Sv)

BR = user-provided breathing rate (m^3 / s)

$DCF_{i,n}$ = user-provided inhalation dose conversion factor for nuclide *n* as discussed in Section 1.4.3.3 (Sv/Bq)

2.3.2 Control Room Consequence Analysis

The dose to a hypothetical individual in the control room is calculated based on the time-integrated concentration in the control room compartment. The air immersion dose in the control room is:

$$D_{c,n}^{CR} = \int C_n(t)dt \left(DCF_{c,n}/G_F\right) \times OF \tag{37}$$

where $C_n(t)$ is the instantaneous concentration of radionuclide n in the compartment. The Murphy–Campe [Mu74] geometric factor, G_f, relates the dose from an infinite cloud to the dose from a cloud of volume V (in $1/m^3$) as:

$$G_F = \frac{351.6}{V^{0.338}} \tag{38}$$

The inhalation dose in the control room is:

$$D_{i,n}^{CR} = \int C(t)dt\left(BR \cdot OF \cdot DCF\right) \tag{39}$$

where OF = user-supplied occupancy factor

The time-dependent atmospheric relative concentration (X/Q) provided by the user for the control room intake locations. The inhalation dose conversion factors have been taken from the output file produced by the FGRDCF code that is based on FGR 11 and 12 and are detailed in Section 1.4.3.3.

2.4 Mathematical Solution Method

This section addresses the mathematical solution method used to ultimately calculate the doses at various locations. The numerical solution technique is discussed in Section 2.4.1. The transport and radioactive decay calculations are discussed in Sections 2.4.2 and 2.4.3, respectively.

2.4.1 Numerical Solution Technique

It is possible to define a single system of coupled ordinary differential equations (ODEs) that simultaneously represents all of the phenomena considered by the code. However, the size of this equation set, and the computational cost of its numerical integration, would make its implementation impractical on a PC. Significant economies of calculation time and computer memory size in RADTRAD are achieved by dividing the calculations into two parts: (1) transport and (2) radioactive decay.

The fundamental premise behind this approach ensures that during a time step of small enough duration, the interdependence of the two components of the calculations can be neglected. That is, the transport equations defining transfer of material between compartments during a calculational time step can be solved numerically without taking account of the radioactive decay and in-growth occurring over that period. Likewise, the radioactive decay and in-growth equations can be solved during a time step without considering the simultaneous phenomenon of transport between compartments. If the user is concerned with the assumption, the scenario can be tested by executing the code with 0.25,1.0, 4.0, and normal time steps to observe the differences; Section 2.4.3 also discusses this effect.