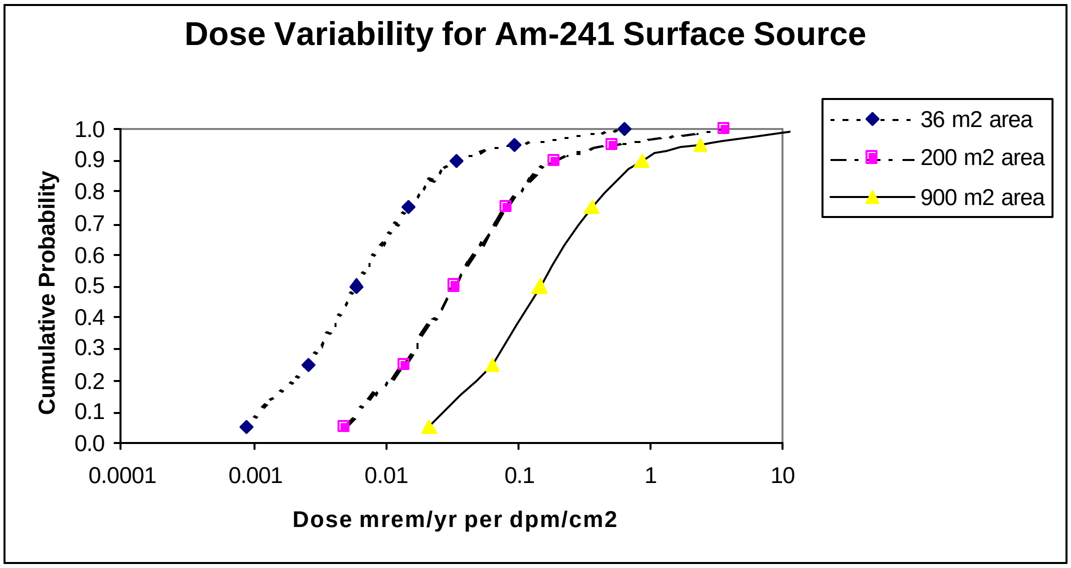

Figure 7.34 Dose Variability of Am-241 for a Surface Source with Three Source Areas in Building Occupancy Scenario

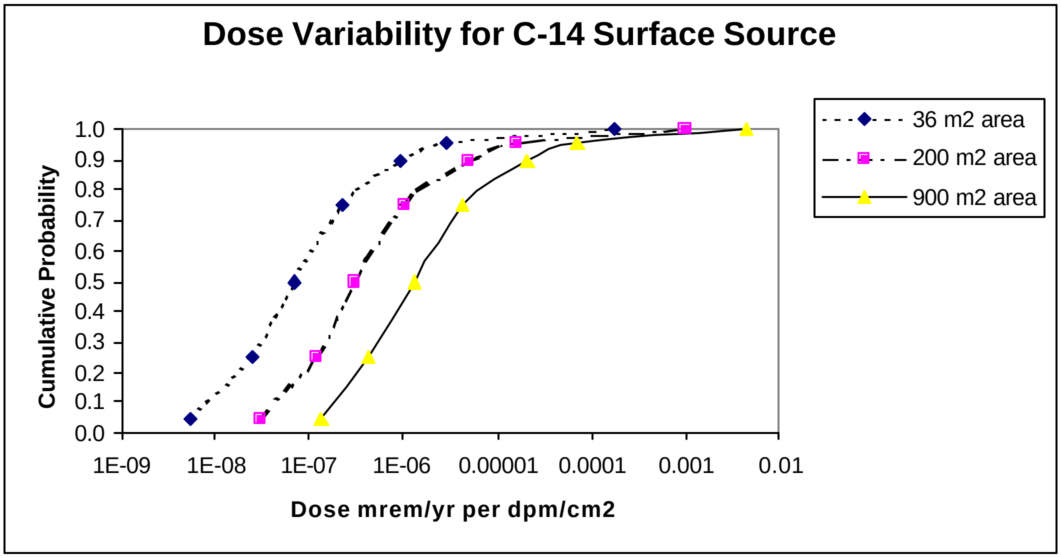

Figure 7.35 Dose Variability of C-14 for a Surface Source with Three Source Areas in Building Occupancy Scenario

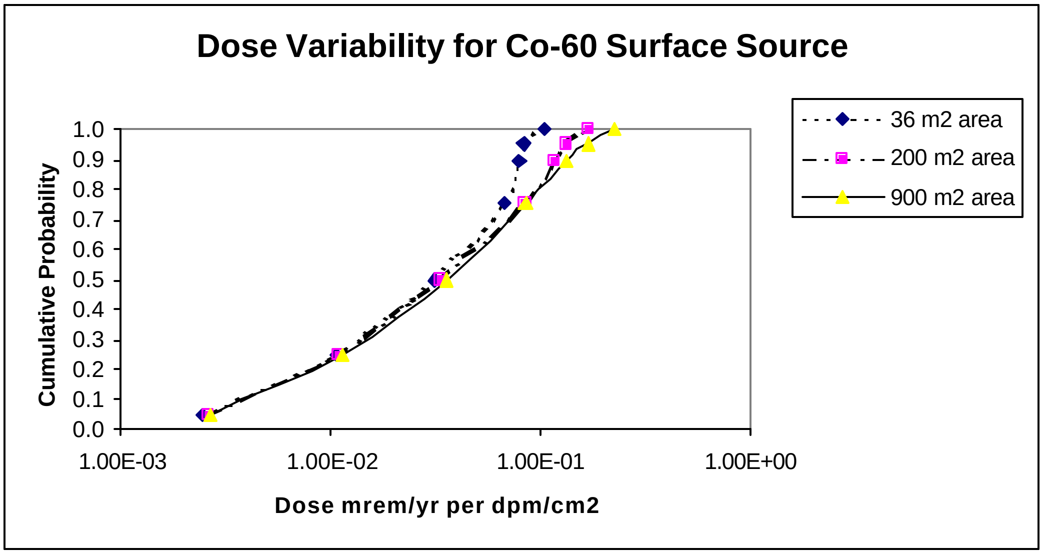

Figure 7.36 Dose Variability of Co-60 for a Surface Source with Three Source Areas in Building Occupancy Scenario

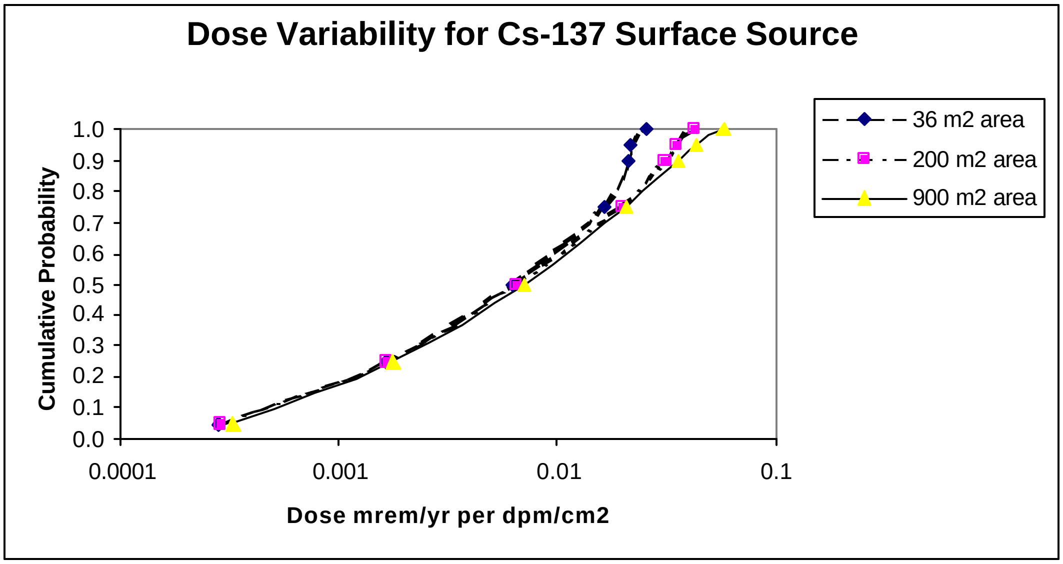

Figure 7.37 Dose Variability of Cs-137 for a Surface Source with Three Source Areas in Building Occupancy Scenario

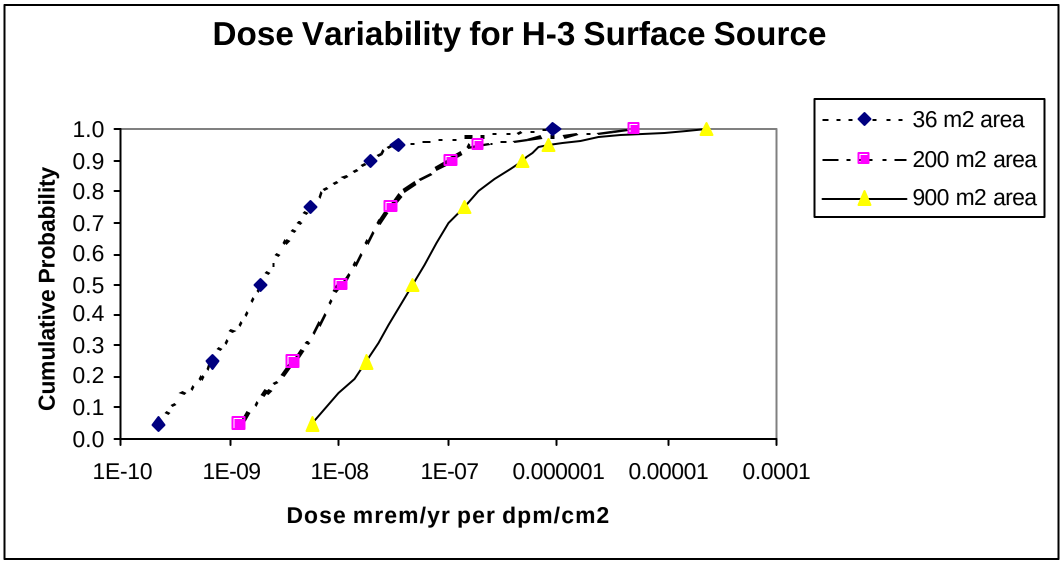

Figure 7.38 Dose Variability of H-3 for a Surface Source with Three Source Areas in Building Occupancy Scenario

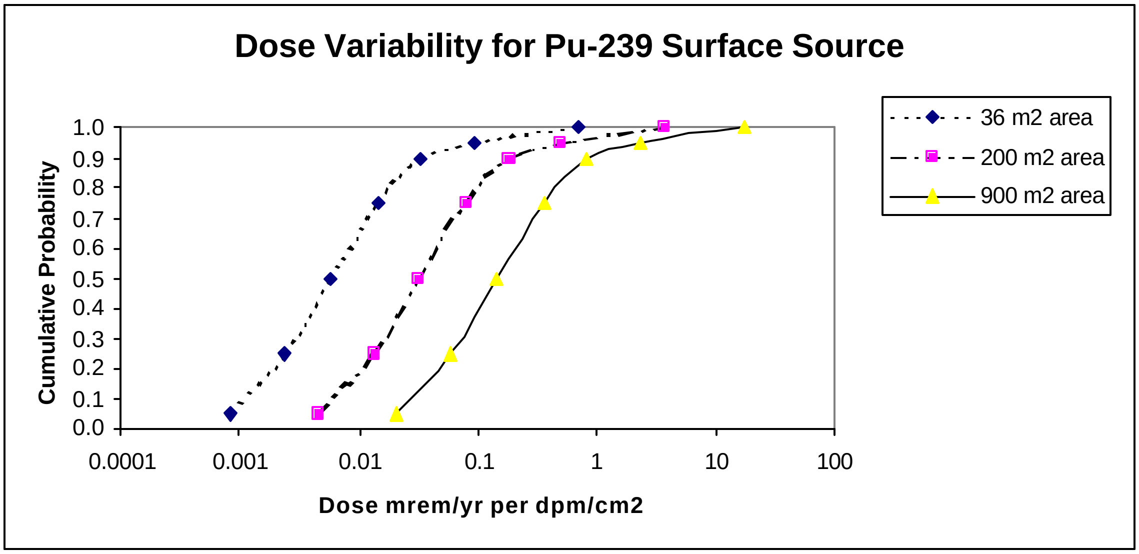

Figure 7.39 Dose Variability of Pu-239 for a Surface Source with Three Source Areas in Building Occupancy Scenario

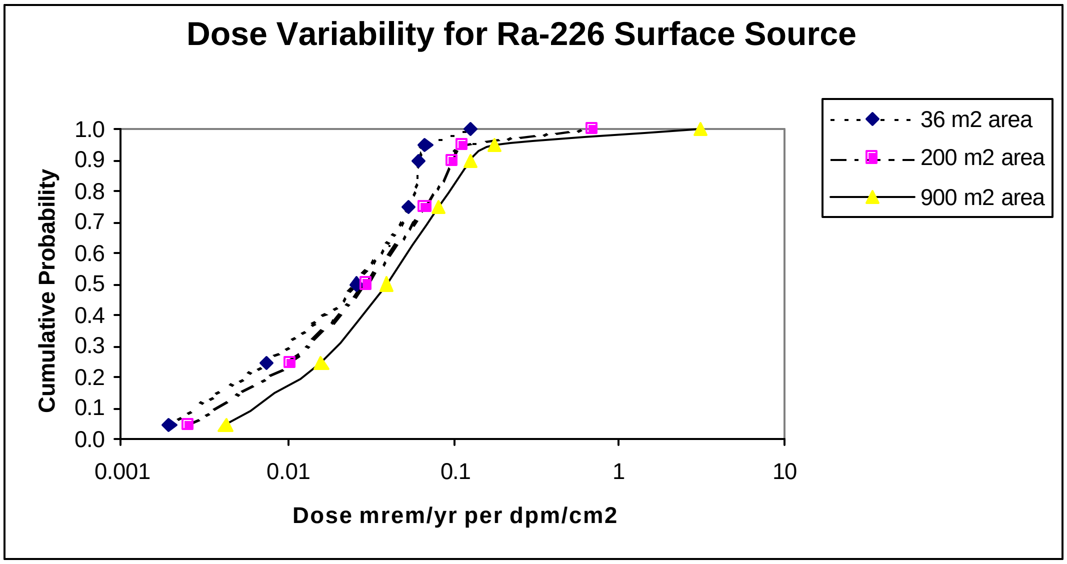

Figure 7.40 Dose Variability of Ra-226 for a Surface Source with Three Source Areas in Building Occupancy Scenario

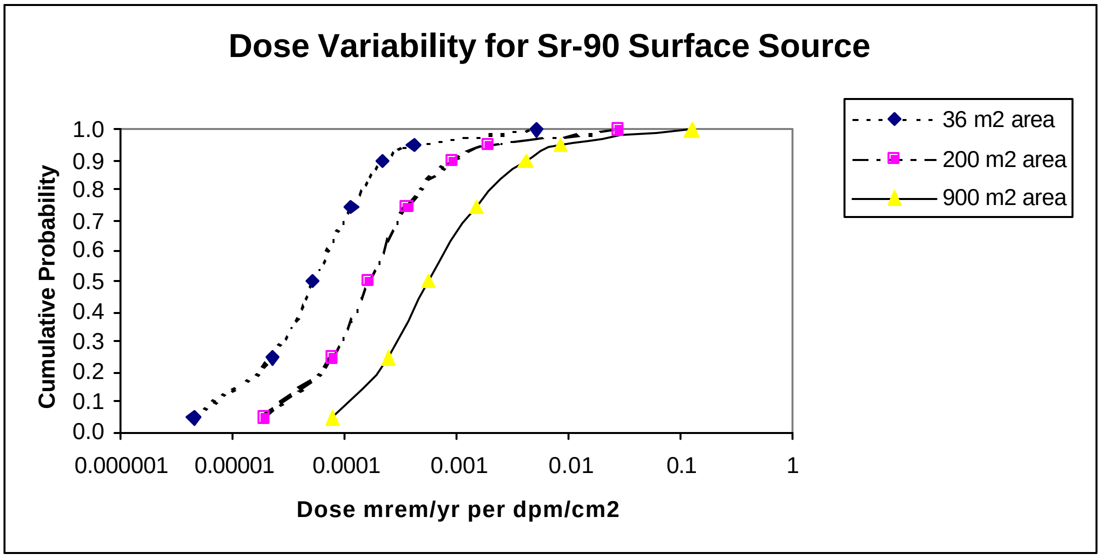

Figure 7.41 Dose Variability of Sr-90 for a Surface Source with Three Source Areas in Building Occupancy Scenario

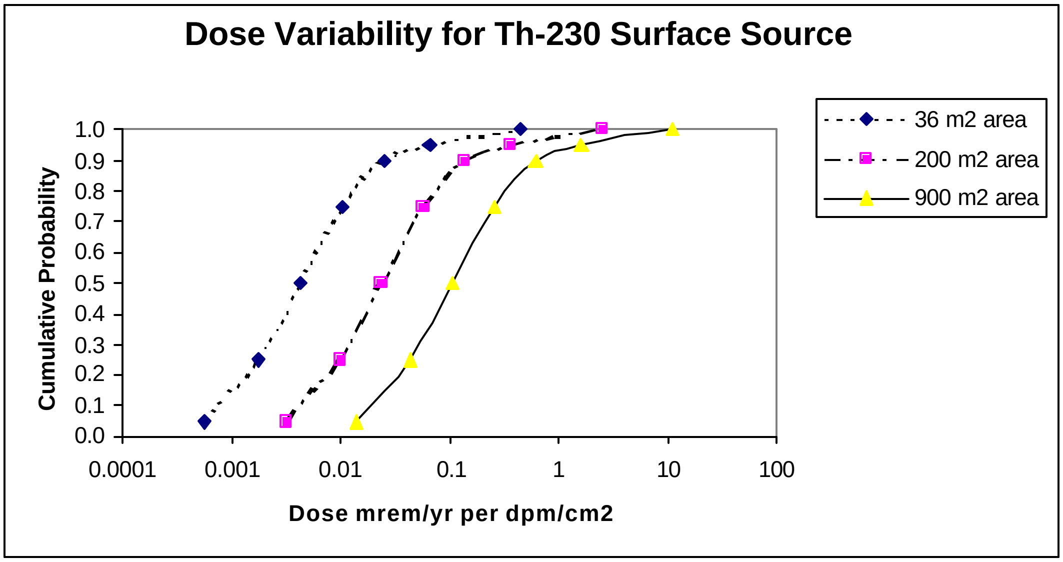

Figure 7.42 Dose Variability of Th-230 for a Surface Source with Three Source Areas in Building Occupancy Scenario

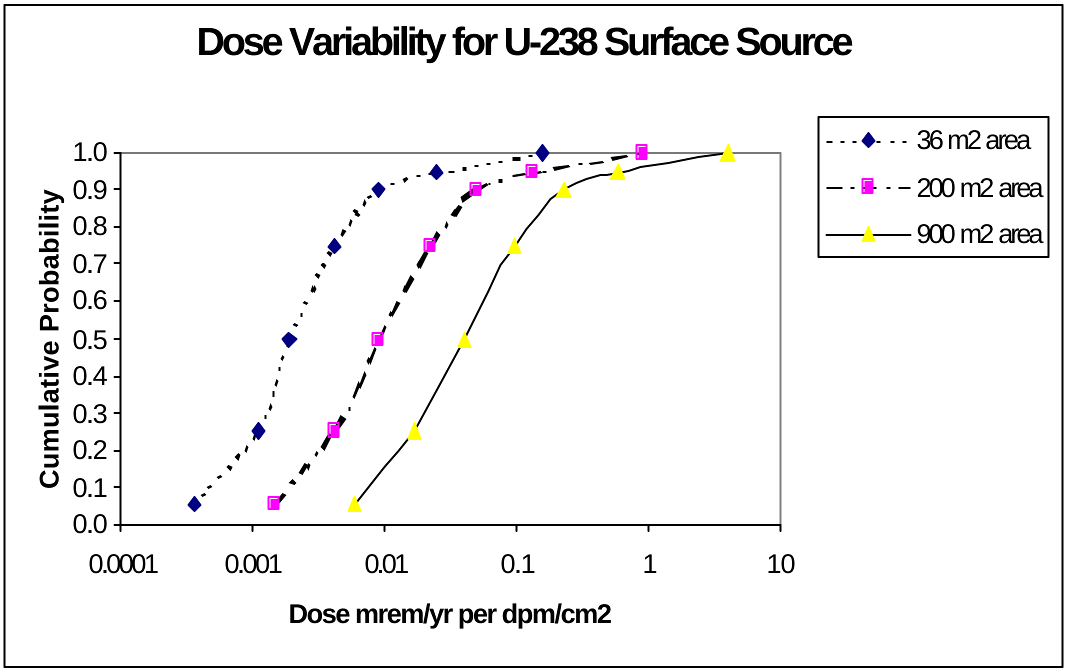

Figure 7.43 Dose Variability of U-238 for a Surface Source with Three Source Areas in Building Occupancy Scenario

Table 7.8. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 36-m^2 Area in a Building Occupancy Scenario					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	**Dominant Pathway[a]**	**1**	**2**	**3**	**4**
Ac-227+D[c]	ext	DSTH	EROS0	AREA	
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH	THICK0		
Am-241	inh + ext	EROS0	DSTH	AREA	H
Am-243+D	ext	DSTH			
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	UD
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH			
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH			
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	DKSUS
Co-57	ext	DSTH			
Co-60	ext	DSTH	THICK0		
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	UD
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	ext	DSTH	EROS0	DKSUS	UD
K-40	ext	DSTH	THICK0		
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH			
Pa-231	ext	DSTH	AREA	EROS0	

Table 7.8. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 36-m^2 Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Pb-210+D	ext	DSTH	EROS0	AREA	DKSUS
Pm-147	ext	DSTH	EROS0	AREA	
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	DSTH
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	UD	DSDEN	
Tc-99	ext	DSTH	EROS0		
Th-228+D	ext	DSTH	THICK0		
Th-229+D	ext	DSTH			
Th-230+D	inh	AREA	EROS0	DSTH	H
Th-232	ext	DSTH	AREA	EROS0	
Tl-204	ext	DSTH	DSDEN		
U-232	ext	DSTH	THICK0		
U-233	inh	EROS0	AREA	DSTH	H
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH			
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH			
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.9. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 200-m^2 Area in a Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	ext	DSTH	AREA	EROS0	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	EROS0	AREA	DSTH	H
Am-243+D	ext	DSTH	EROS0	AREA	
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	AREA
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH			
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH	EROS0	AREA	
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	UD
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	DENSI0
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	ext	EROS0	DSTH	DKSUS	AREA
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH	AREA	EROS0	
Pa-231	ext	DSTH	AREA	EROS0	H

Table 7.9. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 200-m^2 Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Pb-210+D	ext	DSTH	EROS0	AREA	DKSUS
Pm-147	ext	DSTH	EROS0	AREA	
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	AREA	DSDEN	UD
Tc-99	ext	DSTH	EROS0	AREA	DKSUS
Th-228+D	ext	DSTH			
Th-229+D	ext	DSTH	AREA	EROS0	
Th-230+D	inh	EROS0	AREA	H	DSTH
Th-232	ext	DSTH	AREA	EROS0	
Tl-204	ext	DSTH			
U-232	ext	DSTH			
U-233	inh	EROS0	AREA	H	DSTH
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH	AREA		
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH	AREA	EROS0	
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.10. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 900-m^2 Area in a Building Occupancy Scenario					
Radionuclide	**Dominant Pathway**[a]	**Four Most Sensitive Parameters**[b] **Based on SRRC Analysis**			
		1	**2**	**3**	**4**
Ac-227+D[c]	ext	DSTH	EROS0	AREA	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	EROS0	AREA	H	
Am-243+D	ext	DSTH	EROS0	AREA	
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	AREA
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH	EROS0	AREA	
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH	EROS0	AREA	
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	inh + ing	EROS0	DKSUS	AREA	UD
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH	AREA	EROS0	
Pa-231	inh	EROS0	AREA	DSTH	H

Table 7.10. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 900-m^2 Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis 1	2	3	4
Pb-210+D	inh	EROS0	AREA	DKSUS	UD
Pm-147	ext	DSTH	EROS0	AREA	H
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	AREA	EROS0	DSDEN
Tc-99	ext	DSTH	EROS0	AREA	DKSUS
Th-228+D	ext	DSTH			
Th-229+D	ext	DSTH	AREA	EROS0	H
Th-230+D	inh	EROS0	AREA	H	
Th-232	inh + ext	AREA	EROS0	DSTH	H
Tl-204	ext	DSTH			
U-232	ext	DSTH	AREA	EROS0	
U-233	inh	EROS0	AREA	H	
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH	EROS0	AREA	
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH	AREA	EROS0	
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

and without the uncertainty on shielding thickness is shown in Figure 7.44.

For radionuclides for which inhalation was the dominant pathway, room area and source erosion rate were two dominant parameters that contributed to large dose variability. Three radionuclides (Am-241, Cm-244, and Pu-238) were selected to study the effect of room area and erosion rate on the dose variability. Figures 7.45 and 7.46 show the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty on room area and source erosion rate.

7.2.3.2 Dominant Pathways and Sensitive Parameters in Area Source

Tables 7.11 through 7.13 list the four most sensitive parameters based on SRRC along with the dominant pathway for the three sources. Tables C.7 through C.9 in Appendix C present detailed information, including SRRC values. Only sensitive parameters with SRRC values of $0.1 are only listed in these tables. An SRRC value of 0.1 means that one standard deviation change in the parameter value will change the resultant dose by 0.1 times the standard deviation of the dose.

For radionuclides for which external exposure was the dominant pathway, shielding thickness was found to be the dominant contributor to the dose variability. Three radionuclides (Co-60, Al-26, and Eu-152) were selected to study the effect of shielding thickness. It was observed that after removing the shielding thickness from uncertainty analysis, dose variability was significantly reduced. Figure 7.47 shows the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty on shielding thickness.

For radionuclides for which inhalation was the dominant pathway, many parameters (e.g., room area, removable fraction, source lifetime) contributed to the dose variability. Figures 7.48 through 7.50 show the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty for room area, removable fraction, and source lifetime, respectively, for Am-241, Pu-239, and U-238.

For radionuclides with the ingestion pathway as the dominant contributor to the dose, apart from three parameters (room area, removable fraction, source life-time) that contributed to dose variability in the inhalation pathway, deposition velocity and resuspension rate also showed high sensitivity. Figures 7.51 and 7.52 show the effect of deposition velocity and resuspension rate on the dose variability for C-14, I-129, and Cs-135.

7.2.4 Parameter Correlation Results

The results showed that resuspension rate and deposition velocity were sensitive parameters for some radionuclides (e.g., C-14, Ca-41, Cs-135, and I-129) in the case of volume sources. A positive rank correlation of 0.9 was used between deposition velocity and resuspension rate. Four radionuclides (Ca-41, I-129, C-14, and Cs-135) were selected to study the effect of correlation. Figure 7.53 shows the difference in dose variability with and without correlation between deposition velocity and resuspension rate. Dose variability was considerably reduced by the use of correlation. In the absence of knowledge of real correlation between deposition velocity and resuspension rate, rank correlation was not used in the analysis.

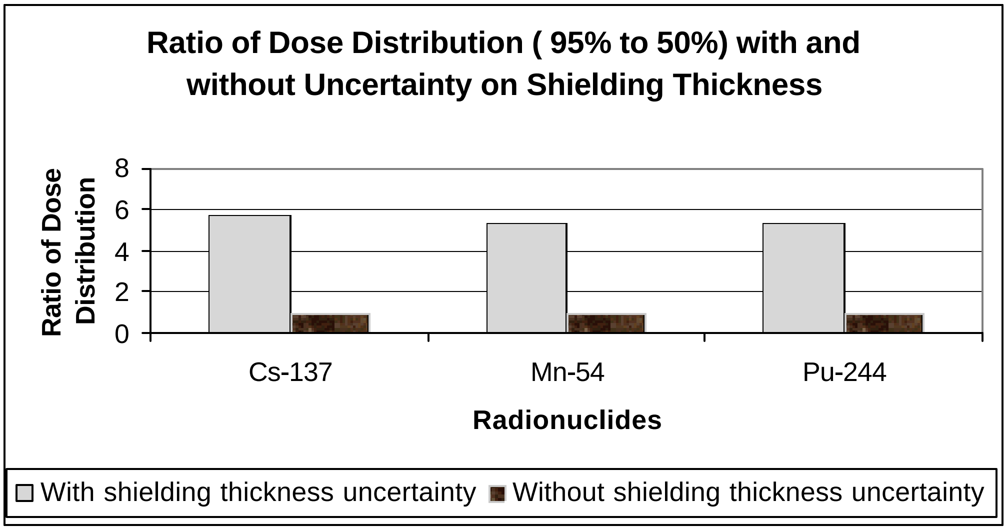

Figure 7.44 Ratio of Dose Distribution with and without Uncertainty on Shielding Thickness for a Volume Source in Building Occupancy Scenario

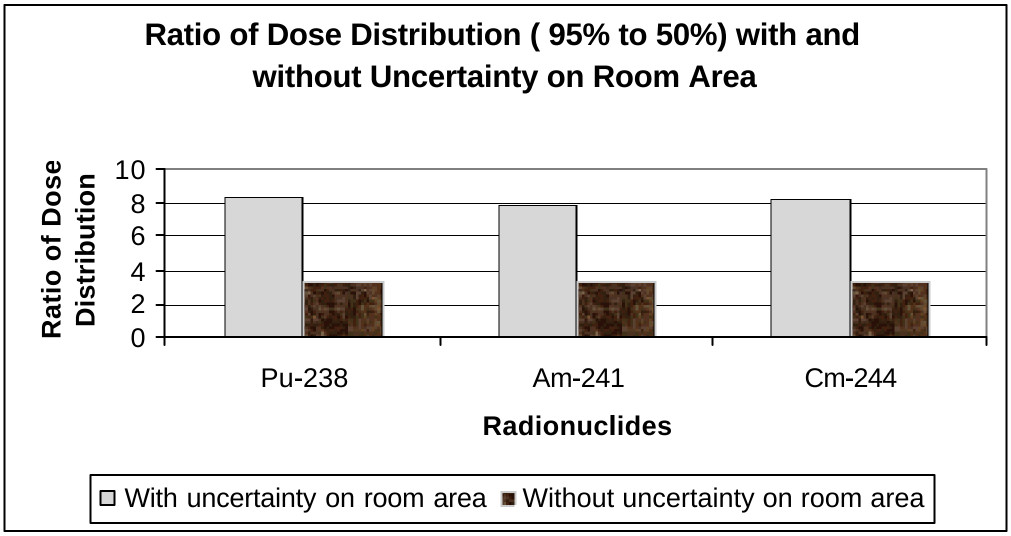

Figure 7.45 Ratio of Dose Distribution with and without Uncertainty on Room Area for a Volume Source in Building Occupancy Scenario

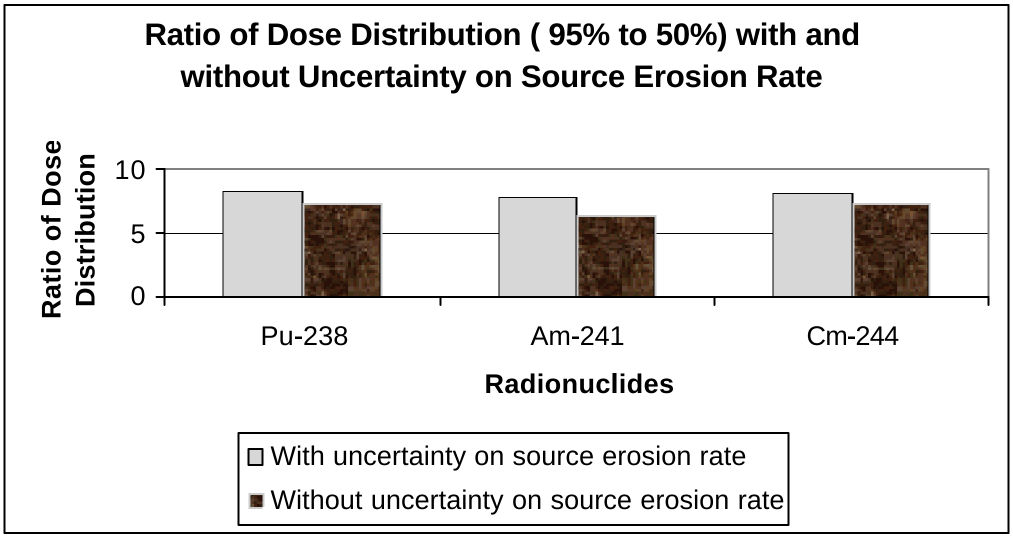

Figure 7.46 Ratio of Dose Distribution with and without Uncertainty on Source Erosion Rate for a Volume Source in Building Occupancy Scenario

Table 7.11. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 36-m^2 Area in a Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	DSTH
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	inh + ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	ext	DSTH	AREA	RF0	RMVFR
Ce-144+D	ext	DSTH			
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	ext	DSTH	AREA	RF0	UD
Cm-243	inh	AREA	RF0	RMVFR	DSTH
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	inh + ing	DKSUS	AREA	RF0	DSTH
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	DSTH
Pa-231	inh	AREA	RF0	RMVFR	H

Table 7.11. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 36-m^2 Area in a Building Occupancy Scenario (Continued)

		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pb-210+D	inh	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	DSTH
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	ext	DSTH	AREA	RF0	RMVFR
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	DSTH	RMVFR
Tc-99	inh + ext	DSTH	AREA	RF0	RMVFR
Th-228+D	ext	DSTH	AREA	RF0	RMVFR
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	DSTH
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh + ext	DSTH	AREA	RF0	RMVFR
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.12. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 200-m^2 Area in a Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	H
Au-195	ext	DSTH	AREA	RF0	RMVFR
Bi-207	ext	DSTH			
C-14	inh + ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	ext	DSTH	AREA	RF0	RMVFR
Ce-144+D	ext	DSTH			
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	ext	DSTH	AREA	RF0	RMVFR
Cm-243	inh	AREA	RF0	RMVFR	H
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	inh + ing	DKSUS	AREA	RF0	RMVFR
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH	AREA	RF0	RMVFR
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH	AREA	RF0	RMVFR
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	inh + ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H

Table 7.12. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 200-m^2 Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	H
Pa-231	inh	AREA	RF0	RMVFR	H
Pb-210+D	inh + ing	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	H
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	inh	AREA	DSTH	RF0	RMVFR
Ra-226+D	ext	DSTH	AREA	RF0	
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	RMVFR	UD
Tc-99	inh	AREA	RF0	RMVFR	DSTH
Th-228+D	ext	DSTH	AREA	RF0	RMVFR
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	H
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh	AREA	RF0	RMVFR	DSTH
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.13. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 900-m^2 Area in a Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	H
Au-195	ext	DSTH	AREA	RF0	RMVFR
Bi-207	ext	DSTH			
C-14	inh +ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	inh	AREA	DSTH	RF0	RMVFR
Ce-144+D	ext	DSTH	AREA	RF0	RMVFR
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	inh	AREA	DSTH	RF0	RMVFR
Cm-243	inh	AREA	RF0	RMVFR	H
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ing	DKSUS	AREA	RF0	RMVFR
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH	AREA	RF0	RMVFR
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH	AREA	RF0	RMVFR
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	inh + ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	H

Table 7.13. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 900-m^2 Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Pa-231	inh	AREA	RF0	RMVFR	H
Pb-210+D	inh + ing	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	H
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	inh	AREA	RF0	RMVFR	H
Ra-226+D	ext	DSTH	AREA	RF0	UD
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH	AREA	RF0	
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	RMVFR	H
Tc-99	inh + ing	AREA	RF0	RMVFR	DKSUS
Th-228+D	inh	AREA	RF0	RMVFR	DSTH
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	H
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh	AREA	RF0	RMVFR	H
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

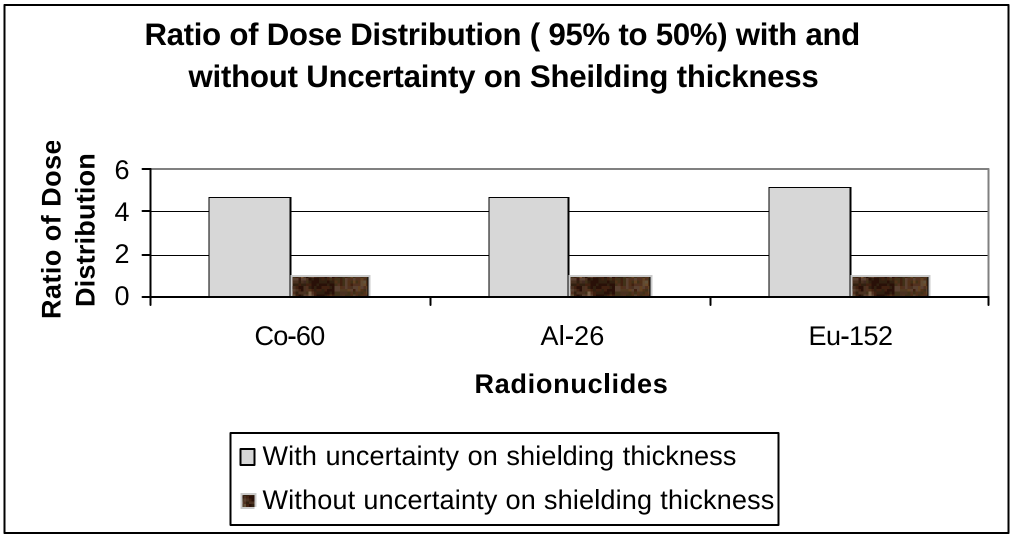

Figure 7.47 Ratio of Dose Distribution with and without Uncertainty on Shielding Thickness for a Surface Source in Building Occupancy Scenario

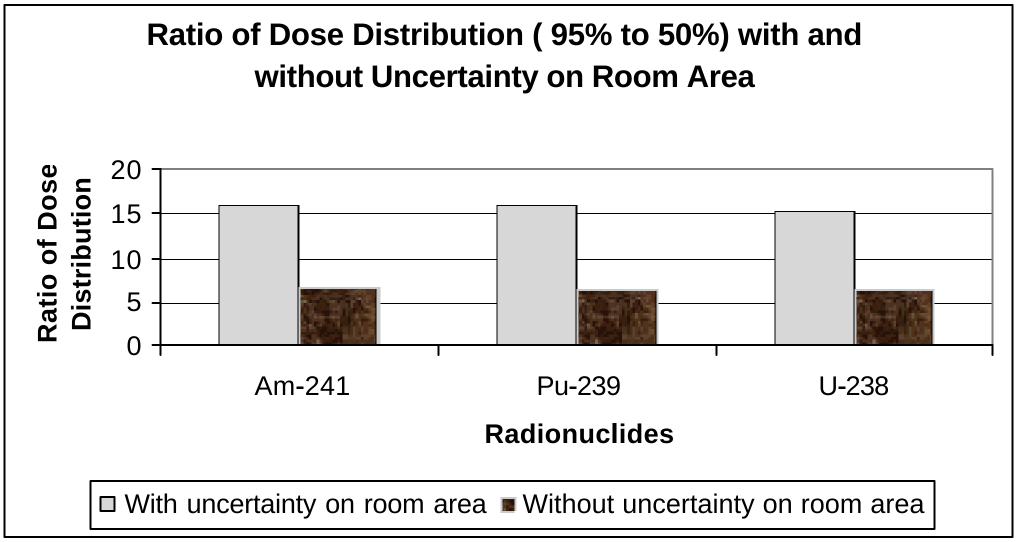

Figure 7.48 Ratio of Dose Distribution with and without Uncertainty on Room Area for a Surface Source in Building Occupancy Scenario

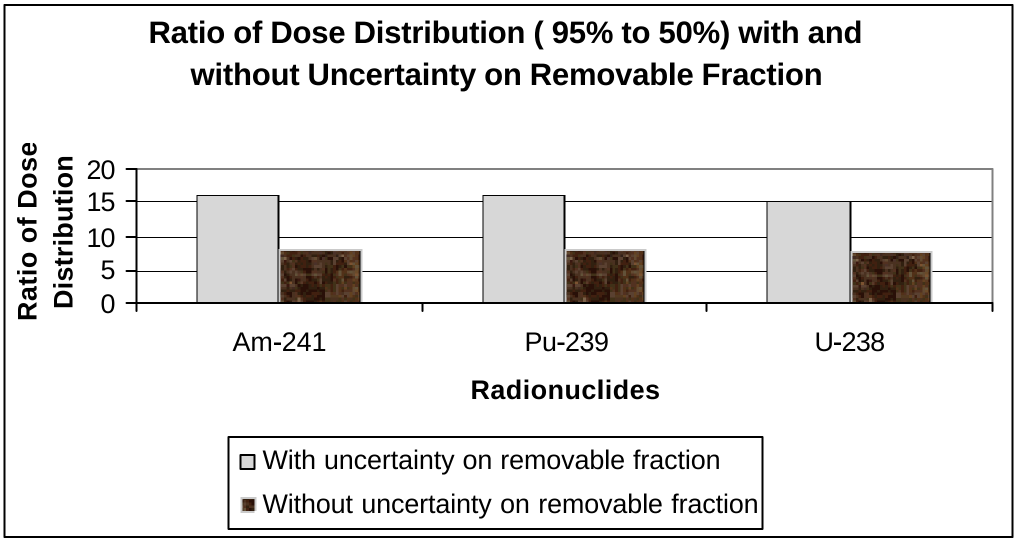

Figure 7.49 Ratio of Dose Distribution with and without Uncertainty on Removable Fraction for a Surface Source in Building Occupancy Scenario

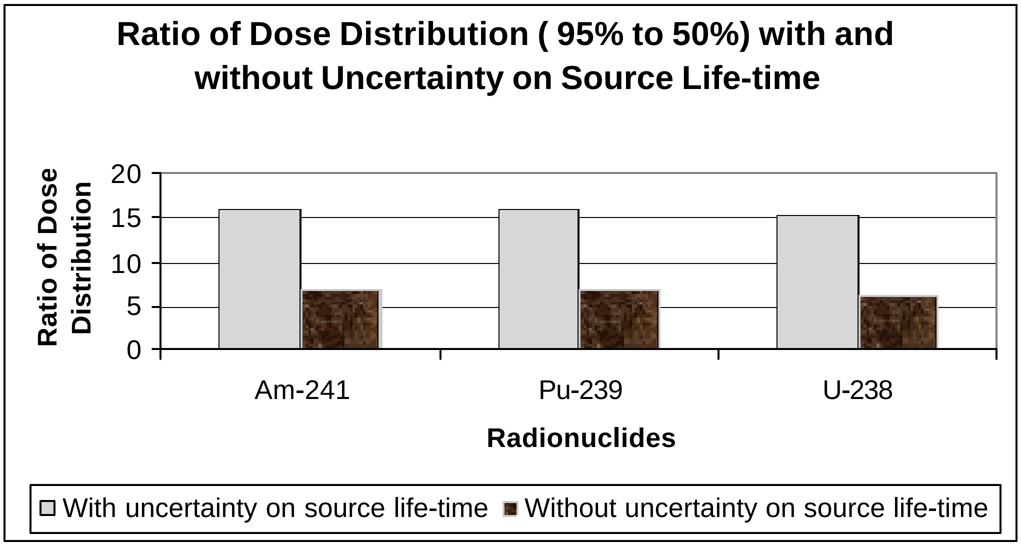

Figure 7.50 Ratio of Dose Distribution with and without Uncertainty on Source Lifetime for a Surface Source in Building Occupancy Scenario

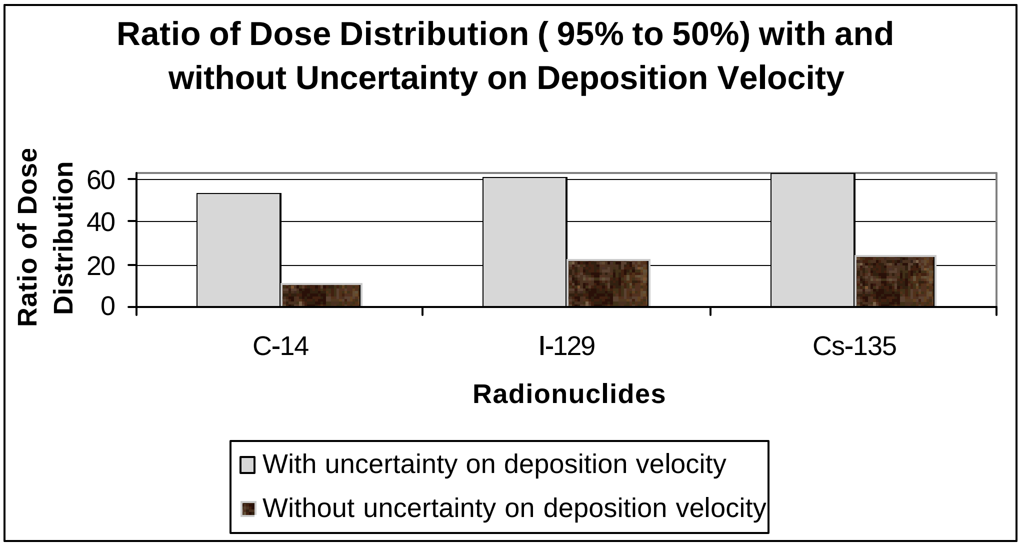

Figure 7.51 Ratio of Dose Distribution with and without Uncertainty on Deposition Velocity for a Surface Source in Building Occupancy Scenario

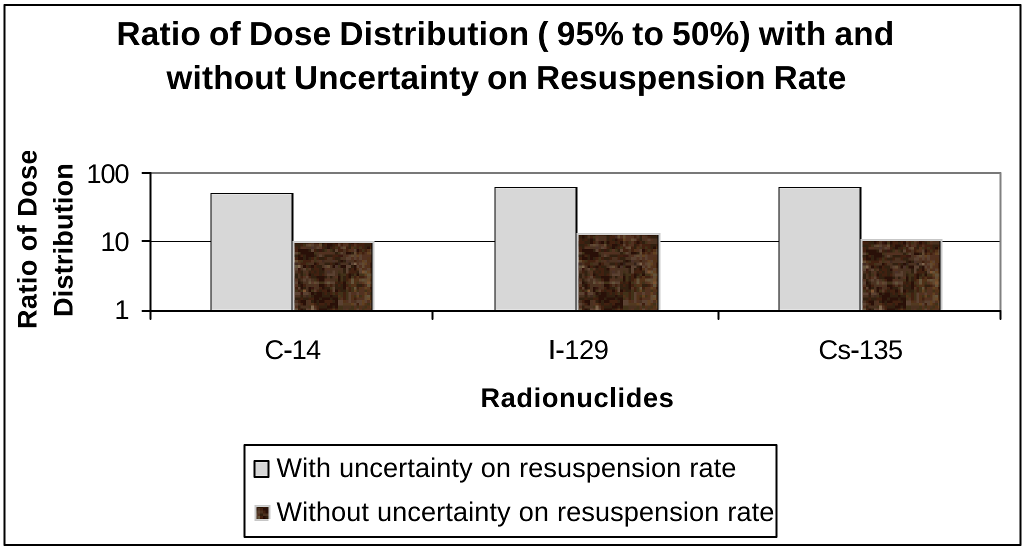

Figure 7.52 Ratio of Dose Distribution with and without Uncertainty on Resuspension Rate for a Surface Source in Building Occupancy Scenario

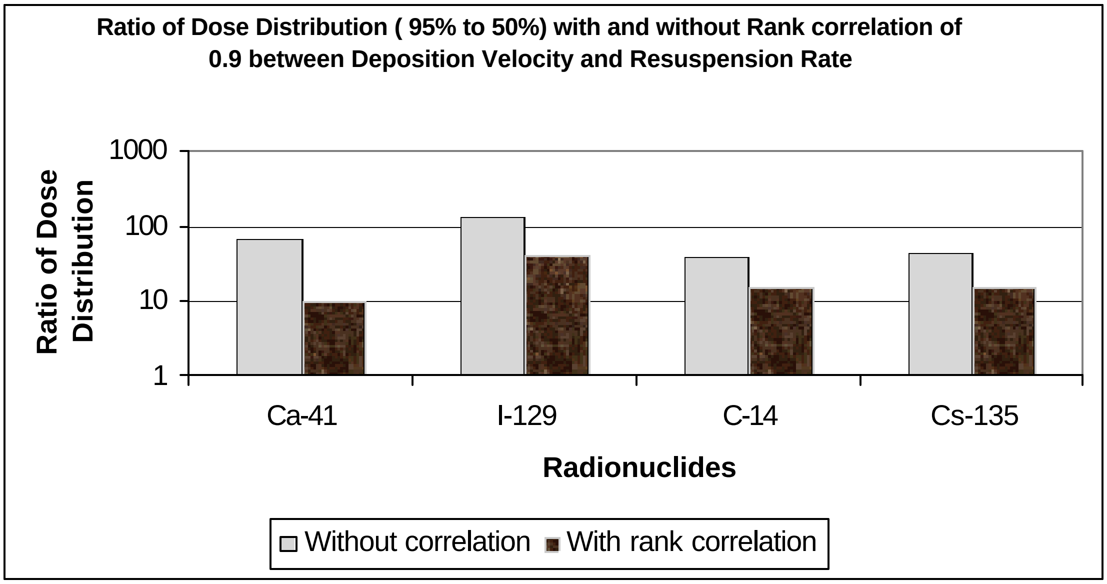

Figure 7.53 Ratio of Dose Distribution with and without Rank Correlation between Deposition Velocity and Resuspension Rate for a Surface Source in Building Occupancy Scenario

8 SUMMARY AND DISCUSSION

The probabilistic dose analysis discussed in this report was conducted to assess the effects of parameter distributions on estimated doses for residual radionuclides as calculated with the RESRAD and RESRAD-BUILD codes for the residential and building occupancy scenarios, respectively. Parameter distributions developed by Biwer et al. (2000) were successfully incorporated into the RESRAD and RESRAD-BUILD codes, and the capability of the two codes to conduct site-specific analyses was tested.

The probabilistic dose analysis was performed by using the stratified sampling of the Latin hypercube sampling (LHS) method to obtain a collection of input distributions. This method provides a rather efficient process for multiparameter sampling. In the analysis, the total effective dose equivalent (TEDE) was estimated for an average member of the critical group under the two scenarios used to assess compliance with the U.S. Nuclear Regulatory Commission's (NRC's) decommissioning and license termination criteria. For RESRAD, the peak dose within a time frame of 1,000 years was captured; for RESRAD-BUILD, the dose at time 0 was computed.

The dose distribution analysis conducted for this report used the generic distributions developed in the Parameter Distribution Report (Biwer et al., 2000) to test the distribution data and to demonstrate the capability of RESRAD and RESRAD-BUILD to perform a site-specific analysis. The specific strategy used to select input values depended on the parameter categories (physical, behavioral, or metabolic). The effect of correlation of input parameter distribution was studied. In cases when a clear relationship was identified (such as bulk density and total porosity and total porosity and effective porosity), strong rank correlations were used.

Some parameters previously identified to be important to dose values (Cheng et al., 1999) were confirmed in the analysis. For RESRAD, such parameters include radionuclide concentrations, source area, and source thickness. For RESRAD-BUILD, these parameters include radionuclide concentrations and source area. To illustrate the sensitivity of the parameters, three source configurations were analyzed for RESRAD: (1) area of 100 m^2 and thickness of 15 cm; (2) area of 2,400 m^2 and thickness of 15 cm; (3) area of 10,000 m^2 and thickness of 2 m. For RESRAD-BUILD, three different areas (36 m^2, 200 m^2, and 900 m^2) were analyzed for area sources, and the same three areas (36 m^2, 200 m^2, and 900 m^2) along with the probability distribution on source thickness were used for volume sources.

Results for the residential scenario indicate that for a change from the baseline configuration (source configuration 1) to an increased area (source configuration 2), a 19-fold increase in the estimated dose could occur, while a change from the baseline case to an extended thickness and area (source configuration 3) could lead a 100-fold increase in the estimated dose. Similarly for the building occupancy scenario, a change in source area could lead to a 25-fold increase in the estimated dose.

Quantile values (at 50th percentile and 90th percentile) of the dose distributions were generated. Dose spread for different radionuclides was identified by the ratio of dose at the 99th percentile to that at the 50th percentile for the residential scenario and by the ratio of dose at the 95th percentile to that at the 50th percentile for the building occupancy scenario. Regression analysis was used to identify sensitive parameters. The partial rank correlation coefficients and standardized rank regression coefficients were used as illustrative examples in the residential and building occupancy scenarios, respectively. The effects of sensitive parameters on distribution were studied for selected radionuclides.

Results demonstrate the successful integration of the parameter distributions developed for the residential and building occupancy scenarios with the probabilistic module developed for the RESRAD and RESRAD-BUILD codes to support NRC's license termination effort. The results demonstrate that the codes and the developed input parameter distributions can be used to accomplish a probabilistic analysis. Application of the process is therefore shown to be feasible for site-specific modeling and analysis in the future when data pertinent to a specific site can be developed.

In a site-specific application, however, some general aspects must be taken into account to ensure accurate modeling and analysis:

- Parameter sensitivity depends on the contamination configuration, and, therefore, it is site specific. It is important that ranking of key parameters be assessed for each individual site.

- Potential correlation between a parameter and the estimated dose varies from radionuclide to radionuclide. Special considerations, experience, and judgment would be needed in obtaining an accurate assessment.

- Site-specific data collection may be needed for parameters consistently identified to be important to the dose analysis in this report.

8.1 HIGHLIGHTS OF RESIDENTIAL SCENARIO RESULTS

- Probabilistic dose analyses for 90 principal radionuclides in three source configurations were performed with distributions for 33 radionuclide-independent parameters and many radionuclide-dependent parameters for the residential scenario.

- Results indicate that the doses calculated appear reasonable and show a consistent pattern. The ratio between the 99th percentile dose and 50th percentile dose ranges from 2.0 to 79 for all radionuclides. Such variations depend on the source configurations and on the type of radionuclide. For radionuclides with a dominant external pathway, the ratio between the 99th percentile dose and 50th percentile dose was close to 2.3 (Ag-108m and Eu-152). For radionuclides with other dominant pathways, dose variabilities were higher. However, site-specific distributions should be used whenever available, especially for sensitive parameters such as the external shielding factor and the plant transfer factor.

- Input rank correlations between total porosity and effective porosity and between bulk density and total porosity were studied, and the results were used in the probabilistic dose analysis to ensure proper pairing between the parameters.

- Significant changes in dose values were observed among the three source configurations (i.e., changes in source thickness or source area resulted in significant changes in dose). For some radionuclides (e.g., Ca-145 and H-3), dose values changed by an order of magnitude. The dose at 90th percentile increased by 12% to 2,900% when the source area changed from 100 m^2 to 2,400 m^2 with a constant source thickness of 15 cm. When the source thickness was changed to 2 m and the source area to 10,000 m^2 from a source thickness of 15 cm and an area of 2,400 m^2, dose at 90th percentile increased by 5% to 2,600%.

- For about 30 radionuclides, the upper 10% of the peak doses occurred at times other than time 0. For these radionuclides, sensitive parameters would change with the dose percentile selected.

- The external shielding factor was the most sensitive parameter in many cases when external exposure was the dominant pathway (this factor accounts for the shielding provided by the structure of the house when the receptor is inside), and the total dose variability could be explained with just the variability in the external shielding factor.

- The plant transfer factor was the most sensitive parameter in many cases when plant ingestion was the dominant pathway (such as for Ca-45 and Cs-135).

- It was observed that no single correlation or regression coefficient (e.g., PRCC, SRRC) can be used alone to identify sensitive parameters in all the cases. The coefficients are useful guides, but they have to be used in conjunction with other aids, such as scatter plots, and must undergo further analysis.

8.2 HIGHLIGHTS OF BUILDING OCCUPANCY SCENARIO RESULTS

- Probabilistic dose analyses were performed for 67 principal radionuclides for two source types (volume and area), with three source areas, with distributions for 15 parameters.

- Results indicate that all parameter distributions are reasonable and consistent for all cases and radionuclides analyzed. However, site-specific distributions should be used whenever available, especially for sensitive parameters.

- Dose variability in the RESRAD-BUILD results for the building occupancy scenario for both volume and area sources was much more than the dose variability observed in RESRAD results for the residential scenario.

- Significant changes (by as much as 25-fold) in dose values were observed with change in source area (from 36 m^2 to 900 m^2) for many radionuclides (such as Cm-244 and Ni-63). For radionuclides with a dominant external pathway (e.g., Co-60, Cs-137), dose changes with source area occurred only at high dose percentile values. Because of shielding between the source and receptor, dose values did not change at low dose percentile values.

- For radionuclides with a dominant external exposure pathway (e.g., Co-60, Cs-137), shielding thickness between the source and receptor was the dominant contributor to the dose variability (ratio between the 95th percentile dose and 50th percentile dose) for volume as well as area sources.

- For radionuclides such as Am-241 and Pu-238 with a dominant inhalation pathway, room area and source erosion rate were the two most sensitive parameters for volume sources. For area sources, the parameters room area, removable fraction, and source lifetime all contributed to the dose variability.

- For a volume source, the ingestion pathway was dominant only for two radionuclides (Ca-41 and H-3). For surface sources, the ingestion pathway was dominant for a few more radionuclides (C-14, Cs-135, I-129).

- For radionuclides with a dominant ingestion pathway (such as C-14 and Cs-135), in addition to the sensitive parameters identified for the inhalation pathway, deposition velocity and resuspension rate also contributed to dose variability.

- When a rank correlation coefficient of 0.9 between deposition velocity and resuspension rate was used, the dose variability was significantly reduced (by a factor of 7).

9 REFERENCES

Beyeler, W.E., et al. NUREG/CR-5512, SAND99-2148, Vol. 3, “Residual Radioactive Contamination from Decommissioning: Parameter Analysis.” Prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission. October 1999.

Biwer, B.M., et al. “Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes, Revision 1.” Letter report prepared by Argonne National Laboratory, Argonne, IL, for U.S. Nuclear Regulatory Commission. March 2000.

Cheng, J.-J., et al. “Selection of RESRAD and RESRAD-BUILD Input Parameters for Detailed Distribution Analysis, Revision 1.” Letter report prepared by Argonne National Laboratory, Argonne, IL, for U.S. Nuclear Regulatory Commission. October 1999.

Cullen, A.C. and H.C. Frey. *Probabilistic Techniques in Exposure Assessment*. Plenum Press: New York, N.Y. 1999.

Haaker, R., et al. NUREG/CR-5512, Vol. 4, “Comparison of Models and Assumptions Used in the DandD 1.0, RESRAD 5.61 and RESRAD-BUILD 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenario Provided in NUREG/CR-5512.” Prepared by Sandia National Laboratories, Albuquerque N.M., for U.S. Nuclear Regulatory Commission. October 1999.

Iman, R.L. and J.C. Helton. NUREG/CR-3904, SAND84-1461 RG, “A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models.” Prepared by Sandia National Laboratories, Albuquerque, N.M., for the U.S. Nuclear Regulatory Commission. March 1985.

Iman, R.L. and M.J. Shortencarier. NUREG/CR-3624, SAND83-2365 RG, “A FORTRAN 77 Program and User’s Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models.” Prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission. March 1984.

Iman, R.L., et al. NUREG/CR-4122, SAND85-0044 RG, “A FORTRAN 77 Program and User’s Guide for the Calculation of Partial Correlation and Standard Regression Coefficients.” Prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission. June 1985.

International Atomic Energy Agency. “Evaluating Reliability of Predictions Made Using Environmental Transfer Models.” Report No. 100. IAEA: Vienna. 1989.

International Commission on Radiological Protection. “Principles of Monitoring for the Protection of the Population.” ICRP Publication 43. Pergamon Press: New York, N.Y. 1984.

Kamboj, S., et al. “Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes.” Letter report prepared by Argonne National Laboratory, Argonne, IL, for U.S. Nuclear Regulatory Commission. September 1999.

Kennedy, W.E. and Strenge, D.L. NUREG/CR-5512, PNL 7994, Vol. 1, “Residual Radioactive Contamination from Decommissioning; A Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent.” Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission. October 1992.

McKay, M.D., et al. “A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code.” *Technometrics,* Vol. 21, pp. 239-245. 1979.

Nuclear Regulatory Commission (U.S.) (NRC). NUREG-1549, “Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination,” Draft Report for Comment, Division of Regulatory Applications, Office of Nuclear Regulatory Research, NRC: Washington, D.C. July 1998a.

Nuclear Regulatory Commission (U.S.) (NRC). Draft Regulatory Guide, DG 4006, “Demonstrating Compliance with the Radiological Criteria for License Termination.” Office of Nuclear Regulatory Research, NRC: Washington, D.C. August 1998b.

Nuclear Regulatory Commission (U.S.) (NRC). NUREG/CP-0163, “Proceedings of the Workshop on Review of Dose Modeling Methods for Demonstration of Compliance With the Radiological Criteria for License Termination.” NRC: Washington, D.C. May 1998c.

Wernig, M.A., et al. NUREG/CR-5512, Vol. 2, “Residual Radioactive Contamination from Decommissioning.” Office of Nuclear Regulatory Research, NRC: Washington, D.C. May 1999.

Yu, C. “RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities.” Chapter 11, pp. 207-231, in: *Decommissioning and Restoration of Nuclear Facilities*. M.J. Slobodien (Ed.). Medical Physics Publishing: Madison, WI. 1999.

Yu, C., et al. “Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0.” ANL/EAD/LD-2. Argonne National Laboratory: Argonne, IL. September 1993.

Yu, C., et al. “RESRAD-BUILD: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material.” ANL/EAD/LD-3. Argonne National Laboratory: Argonne, IL. November 1994.