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Rev. 0

Key Words: Dose Conversion Factor, Maximum Contaminant Level, Special Analysis

Retention: Permanent

Radionuclide Data Package for Performance Assessment Calculations Related to the E-Area Low-Level Waste Facility at the Savannah River Site

James R. Cook

March 20, 2007

Savannah River National Laboratory
Washington Savannah River Company
Savannah River Site
Aiken, SC 29808

Prepared for the U.S. Department of Energy Under Contract Number DE-AC09-96SR18500

SRNL

REVIEWS AND APPROVALS

Author

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James R. Cook, Author, SRNL — Date

Approvals and Reviews

Elmer L. Wilhite, Internal Review (per WSRC-IM-2002-00011, Rev. 2), SRNL — Date

Maurice J.Ades, Internal Design Check (per WSRC-IM-2002-00011, Rev. 2,) WMAP — Date

B.T. Butcher, Level 4 Manager, SRNL — Date

W. E. Stevens, Level 3 Manager, SRNL — Date

W. T. Goldston, Waste Management Area Project — Date

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U.S. Department of Energy

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Acronyms

PA	Performance Assessment
SRS	Savannah River Site

1.0 ABSTRACT

The Savannah River Site disposes of low-level radioactive waste within on-site engineered disposal facilities. The Savannah River Site must demonstrate that these disposals meet the requirements of DOE Order 435.1 through a process known as performance assessment (PA). The objective of this document is to provide the radionuclide-specific data needed for the PA calculations. This work is part of an on-going program to periodically review and update existing PA work as new data becomes available. Revision of the E-Area Low-Level Waste Facility PA is currently underway.

The number of radionuclides selected to undergo detailed analysis in the PA is determined by a screening process. The basis of this process is described.

Radionuclide-specific data for half-lives, decay modes, daughters, dose conversion factors and groundwater concentration limits are presented with source references and methodologies.

2.0 OBJECTIVE AND SCOPE

The objectives of this document are to explain the following as they relate to performance assessments conducted at the Savannah River Site:

1. the radionuclide screening methodology,
2. the source documents used for radionuclide-specific values for the numerical parameters and justification for their selection,
3. the radionuclide-specific input values for the PA and justification for their selection, and
4. the review process of this document

The scope of this document is to provide radionuclide-specific input values for PA modeling at the Savannah River Site.

3.0 PHILOSOPHY AND ASSUMPTIONS

A basic philosophy of the PA at SRS is to use screening processes to reduce the number of radionuclides for which detailed calculations must be performed. This is done using a combination of a conservative, high-level model and site-specific process knowledge for the groundwater and atmospheric pathways as well as for hypothetical intruder scenarios.

Sections 3.1 through 3.3 describe the philosophy and assumptions that are used in the groundwater, atmospheric and intruder pathway screening, respectively. Section 3.4 describes the methodology used to calculate groundwater concentration limits for those radionuclides without a published Safe Drinking Water Act Maximum Contaminant Level.

3.1 Groundwater Pathway Screening

The methodology developed by the National Council on Radiological Protection and Measurements (NCRP 1996) described in Section 4.2.2 of Volume 1 of that report was used to reduce the number of radionuclides requiring detailed analysis of the groundwater pathway from 826 to 86 (Taylor and Collard 2005). The list was further reduced to 35 radionuclides by considering only those radionuclides with a total disposed inventory in all E-Area disposal units (Stallings and Swingle 2005) that exceeds the trigger values calculated in Taylor and Collard 2005 (Cook 2006). Trigger values are the inventory of a radionuclide that would give a dose of 0.04 mrem/year using the NCRP screening methodology. The 35 radionuclides are the parent radionuclides used in the groundwater transport calculations. A number of data tables have been included in this report. Table A-1 lists the 826 radionuclides considered in the PA process. Table A-2 lists the 86 radionuclides remaining after groundwater screening. Table A-3 lists the 35 parent radionuclides that were used in the groundwater transport calculations.

3.2 Atmospheric Pathway Screening

The methodology for reducing the number of radionuclides requiring detailed analysis of the atmospheric pathway relied on the following:

1. Applying the screening methodology developed by the National Council on Radiological Protection and Measurements (NCRP 1996) described in Section 2.2.1 of Volume 1 of that report and calculating trigger values (inventory that would give a dose of 0.1 mrem/year),
2. Removing from consideration all but those elements and associated radionuclides that could be released from a closed E-Area disposal unit in the vapor phase and
3. Eliminating from consideration those volatile radionuclides that are not currently found in the E-Area Low-Level Waste Facility or were below trigger values calculated in the first screening step.

When this screening process was completed the number of radionuclides requiring detailed analysis of the atmospheric pathway was reduced from 826 to 15 (Crapse and Cook 2006). Table A-4 is a list of these 15 radionuclides.

3.3 Intruder Scenario Screening

The methodology developed by the National Council on Radiological Protection and Measurements (NCRP 1996) described in Section 4.2.3 of Volume 1 of that report was used to reduce the number of radionuclides requiring detailed analysis of intruder scenarios from 826 to 78 parent radionuclides (Cook and Wilhite 2004). These radionuclides were then included in a computer application that calculates intruder-based disposal limits for each disposal unit in E-Area (Koffman 2004). Table A-5 lists these 78 parent radionuclides.

3.4 Groundwater Concentration Limits

When available, groundwater concentration limits provided by the USEPA as a part of the Safe Drinking Water Act are used (USEPA 1992). For the remainder of the radionuclides, groundwater concentration limits were calculated using the dose conversion factors in Federal Regulatory Guidance 11 (Eckerman 1988), a drinking water consumption rate of 730 liters/year and a dose limit if 4 mrem/year:

$$\text{Limit (pCi/L)} = 4\ \text{mrem/yr} / (\text{DCF (mrem/pCi)} * 730\ \text{L/yr})$$

These are given in Table A-6.

3.5 Abbreviated Radionuclide Decay Chains in Groundwater Analysis

The ELLWF PA Revision Core team agreed to exclude from the groundwater transport analysis those radioactive daughter isotopes with half-lives less than 5 years. This was done to reduce the number of radionuclides modeled. A detailed analysis was not done; rather, it was judged that neglecting these daughters would not compromise the results of the analysis. The assumption was not strictly based on the concept of secular equilibrium, but was a practical judgment to facilitate the transport analysis. The subsequent dose analysis uses all of the daughters.

Using the RadDecay® software, there are a total of 45 radioactive daughters, with half-lives less than five years, from the 35 parent radionuclides that are to be analyzed in the groundwater analysis (Section 3.1). These daughters range in half-life from 1.9 years for Th-228 to 3E-7 seconds for Po-212.

The 35 parent radionuclides were considered to check on the potential significance of daughters with half-lives less than 5 years. Of the 35 parents, 10 (C-14, Cl-36, H-3, I-129, K-40, Nb-94, Ni-59, Pd-107, Se-79, and Tc-99) have daughters that are stable. Two of the parents (Mo-93 and Zr-93) decay to Nb-93m, whose half-life is 14.6 years and which subsequently decays to Nb-93, which is stable. The chains for the remaining parents were examined to consider the difference in half-life between the first daughter whose half-life is less than 5 years and its parent. These ratios range from 1.2E-04 for Cm-244, Pu-240, Th-232 and U-236 to 4.1E-12 for Pu-239 and U-235. The ratio of half-lives equals the ratio of the radioactivity (i.e., curies) of the daughter and parent. For those radionuclides whose half-life ratio is 1.2E-04, the short-lived daughters are no more than 0.012% of the parent's radioactivity. Thus, these and subsequent daughters are judged not to be significant in the transport analysis.

4.0 REGULATORY FRAMEWORK AND DATA SOURCES

4.1 DOE Order 435.1

The specific performance objectives for solid waste disposal in E-Area are contained in USDOE Order 435.1 (USDOE 1999):

> Performance Objectives. Low-level waste disposal facilities shall be sited, designed, operated, maintained, and closed so that a reasonable expectation exists that the following performance objectives will be met for waste disposed of after September 26, 1988:
>
> (a) Dose to representative members of the public shall not exceed 25 mrem (0.25 mSv) in a year total effective dose equivalent from all exposure pathways, excluding the dose from radon and its progeny in air.
>
> (b) Dose to representative members of the public via the air pathway shall not exceed 10 mrem (0.10 mSv) in a year total effective dose equivalent, excluding the dose from radon and its progeny.
>
> (c) Release of radon shall be less than an average flux of 20 $pCi/m^2/s$ (0.74 $Bq/m^2/s$) at the surface of the disposal facility. Alternatively, a limit of 0.5 pCi/L (0.0185 Bq/L) of air may be applied at the boundary of the facility.

In addition to the performance objectives, the Order requires an assessment of impacts to water resources and to hypothetical persons assumed to inadvertently intrude for a temporary period into the low-level waste disposal facility. Table 1 is a summary of these requirements

4.2 Environmental Protection Agency Safe Drinking Water Act

The guidance for implementation of the Safe Drinking Water Act published by the USEPA is used as the primary source for groundwater concentration limits (USEPA 2002). These consist of published Maximum Contaminant Levels for beta-gamma radionuclides, 15 pCi/L for alpha-emitting radionuclides and 30 μg/L for each uranium isotope.

5.0 DATA TABLES

The radionuclide data to be used in the E-Area Performance Assessment conducted in 2006 and 2007 are given in Tables A-1 through A-10 in Appendix A. The PA relies on a consistent application of radionuclide properties throughout the analysis. The data tables gives references for the sources of radionuclide data. In addition to the tables already described, the following are presented in Appendix A. Radionuclide half lives and branching fractions as given in Table A-7, information on whether a transformation is by alpha decay or not for branching fractions greater than or equal to 0.01, which is needed to determine a groundwater concentration limit, is found in Table A-8, ingestion effective dose conversion factors are shown in three sets of units in Table A-9, the radioactive decay constants are given in Table A-10, and the values of Moles/Ci and g/Ci for each radionuclide of interest in the groundwater transport calculations (parents and daughters with a half-life greater than 5 years), calculated using the equations

Curies per mole = (Avagadro's Number * natural log of 2) / (Radionuclide half life) / (disintegrations per year per Curie)

and

Curies per gram = Curies per mole / grams per mole

are presented in Table A-11.

6.0 REVIEW PROCESS

This report provides baseline data being used in the E-Area PA revision. The objective of the review process is not only to improve the quality of this document, but also to enhance its credibility. Performance Assessments must undergo a number of evaluations, including technical reviews from the outside scientific community. The internal review process will be based on the SRNL Technical Report Design Check Guidelines (WSRC-IM-2002-00011, Rev.2)

All review instructions, comments, and manner in which the review comments were addressed will be documented and archived. The process will be taken full cycle, *i.e.,* all comments will be resolved to the reviewers' satisfaction.

Table 1 Performance Objectives, Assessment Requirements, and Points of Compliance From DOE Order 435.1

Performance Objective[1]	Measure	Point of Compliance
All pathways	$\leq$25 mrem in a year, not including doses from radon and its progeny in air	Point of highest projected dose or concentration beyond a 100-meter buffer zone surrounding the disposed waste.
Air pathway	$\leq$10 mrem in a year, not including doses from radon and progeny	Point of highest projected dose or concentration beyond a 100-meter buffer zone surrounding the disposed waste.
Radon	either	
	(1) an average flux of $\leq$ 20 pCi/m^2/s, or	Disposal facility surface
	(2) an air concentration of $\leq$ 0.5 pCi/L	Point of highest projected dose or concentration beyond a 100-meter buffer zone surrounding the disposed waste.
Assessment Requirement[2]	**Measure**	**Point of Compliance**
Hypothetical inadvertent intruder	100 mrem in a year from chronic exposure	Disposal facility
	500 mrem from a single event	Disposal facility
Impact on Water Resources	The SRS interpretation is that concentrations of radioactive contaminants should not exceed standards for public drinking water supplies established by the USDOE (40 CFR Part 141).	Point of highest projected dose or concentration beyond a 100 meter buffer zone surrounding the disposed waste.

1. USDOE Order 435.1 requires that low-level waste disposal facilities shall be sited, designed, operated, maintained, and closed so that a reasonable expectation exists that the performance objectives will be met for waste disposed of after September 26, 1988.

2. USDOE Order 435.1 also requires that the performance assessment include, for purposes of establishing limits on radionuclides that may be disposed of near-surface, an assessment of the impacts on water resources and an assessment of impacts calculated for a hypothetical person assumed to inadvertently intrude for a temporary period into the low-level waste disposal facility.

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APPENDIX A

Table A-1 Radionuclides to be Considered in the PA Process (ICRP 1983)

Ac-223	As-70	Bi-202	Cd-117m	Co-61
Ac-224	As-71	Bi-203	Ce-134	Co-62m
Ac-225	As-72	Bi-205	Ce-135	Cr-48
Ac-226	As-73	Bi-206	Ce-137	Cr-49
Ac-227	As-74	Bi-207	Ce-137m	Cr-51
Ac-228	As-76	Bi-210	Ce-139	Cs-125
Ag-102	As-77	Bi-210m	Ce-141	Cs-126
Ag-103	As-78	Bi-211	Ce-143	Cs-127
Ag-104	At-207	Bi-212	Ce-144	Cs-128
Ag-104m	At-211	Bi-213	Cf-244	Cs-129
Ag-105	At-215	Bi-214	Cf-246	Cs-130
Ag-106	At-216	Bk-245	Cf-248	Cs-131
Ag-106m	At-217	Bk-246	Cf-249	Cs-132
Ag-108	At-218	Bk-247	Cf-250	Cs-134
Ag-108m	Au-193	Bk-249	Cf-251	Cs-134m
Ag-109m	Au-194	Bk-250	Cf-252	Cs-135
Ag-110	Au-195	Br-74	Cf-253	Cs-135m
Ag-110m	Au-195m	Br-74m	Cf-254	Cs-136
Ag-111	Au-198	Br-75	Cl-36	Cs-137
Ag-112	Au-198m	Br-76	Cl-38	Cs-138
Ag-115	Au-199	Br-77	Cl-39	Cu-60
Al-26	Au-200	Br-80	Cm-238	Cu-61
Al-28	Au-200m	Br-80m	Cm-240	Cu-62
Am-237	Au-201	Br-82	Cm-241	Cu-64
Am-238	Ba-126	Br-83	Cm-242	Cu-66
Am-239	Ba-128	Br-84	Cm-243	Cu-67
Am-240	Ba-131	C-11	Cm-244	Dy-155
Am-241	Ba-131m	C-14	Cm-245	Dy-157
Am-242	Ba-133	Ca-41	Cm-246	Dy-159
Am-242m	Ba-133m	Ca-45	Cm-247	Dy-165
Am-243	Ba-135m	Ca-47	Cm-248	Dy-166
Am-244	Ba-137m	Ca-49	Cm-249	Er-161
Am-244m	Ba-139	Cd-104	Cm-250	Er-165
Am-245	Ba-140	Cd-107	Co-55	Er-169
Am-246	Ba-141	Cd-109	Co-56	Er-171
Am-246m	Ba-142	Cd-113	Co-57	Er-172
Ar-37	Be-10	Cd-113m	Co-58	Es-250
Ar-39	Be-7	Cd-115	Co-58m	Es-251
Ar-41	Bi-200	Cd-115m	Co-60	Es-253
As-69	Bi-201	Cd-117	Co-60m	Es-254

Table A-1 Radionuclides to be Considered in the PA Process (ICRP 1983)

Es-254m	Gd-148	Ho-159	In-119m	La-137
Eu-145	Gd-149	Ho-161	Ir-182	La-138
Eu-146	Gd-151	Ho-162	Ir-184	La-140
Eu-147	Gd-152	Ho-162m	Ir-185	La-141
Eu-148	Gd-153	Ho-164	Ir-186a	La-142
Eu-149	Gd-159	Ho-164m	Ir-186b	La-143
Eu-150a	Ge-66	Ho-166	Ir-187	Lu-169
Eu-150b	Ge-67	Ho-166m	Ir-188	Lu-170
Eu-152	Ge-68	Ho-167	Ir-189	Lu-171
Eu-152m	Ge-69	I-120	Ir-190	Lu-172
Eu-154	Ge-71	I-120m	Ir-190m	Lu-173
Eu-155	Ge-75	I-121	Ir-190n	Lu-174
Eu-156	Ge-77	I-122	Ir-191m	Lu-174m
Eu-157	Ge-78	I-123	Ir-192	Lu-176
Eu-158	H-3	I-124	Ir-192m	Lu-176m
F-18	Hf-170	I-125	Ir-194	Lu-177
Fe-52	Hf-172	I-126	Ir-194m	Lu-177m
Fe-55	Hf-173	I-128	Ir-195	Lu-178
Fe-59	Hf-174	I-129	Ir-195m	Lu-178m
Fe-60	Hf-175	I-130	K-38	Lu-179
Fm-252	Hf-177m	I-131	K-40	Md-257
Fm-253	Hf-178m	I-132	K-42	Md-258
Fm-254	Hf-179m	I-132m	K-43	Mg-28
Fm-255	Hf-180m	I-133	K-44	Mn-51
Fm-257	Hf-181	I-134	K-45	Mn-52
Fr-219	Hf-182	I-135	Kr-74	Mn-52m
Fr-220	Hf-182m	In-109	Kr-76	Mn-53
Fr-221	Hf-183	In-110a	Kr-77	Mn-54
Fr-222	Hf-184	In-110b	Kr-79	Mn-56
Fr-223	Hg-193	In-111	Kr-81	Mo-101
Ga-65	Hg-193m	In-112	Kr-81m	Mo-90
Ga-66	Hg-194	In-113m	Kr-83m	Mo-93
Ga-67	Hg-195	In-114	Kr-85	Mo-93m
Ga-68	Hg-195m	In-114m	Kr-85m	Mo-99
Ga-70	Hg-197	In-115	Kr-87	N-13
Ga-72	Hg-197m	In-115m	Kr-88	Na-22
Ga-73	Hg-199m	In-116m	La-131	Na-24
Gd-145	Hg-203	In-117	La-132	Nb-88
Gd-146	Ho-155	In-117m	La-134	Nb-89a
Gd-147	Ho-157	In-119	La-135	Nb-89b

Table A-1 Radionuclides to be Considered in the PA Process (ICRP 1983)

Nb-90	Os-185	Pm-144	Pt-197m	Re-182b
Nb-93m	Os-189m	Pm-145	Pt-199	Re-184
Nb-94	Os-190m	Pm-146	Pt-200	Re-184m
Nb-95	Os-191m	Pm-147	Pu-234	Re-186
Nb-95m	Os-191	Pm-148	Pu-235	Re-186m
Nb-96	Os-193	Pm-148m	Pu-236	Re-187
Nb-97	Os-194	Pm-149	Pu-237	Re-188
Nb-97m	P-30	Pm-150	Pu-238	Re-188m
Nb-98	P-32	Pm-151	Pu-239	Re-189
Nd-136	P-33	Po-203	Pu-240	Rh-100
Nd-138	Pa-227	Po-205	Pu-241	Rh-101
Nd-139	Pa-228	Po-207	Pu-242	Rh-101m
Nd-139m	Pa-230	Po-210	Pu-243	Rh-102
Nd-141	Pa-231	Po-211	Pu-244	Rh-102m
Nd-141m	Pa-232	Po-212	Pu-245	Rh-103m
Nd-147	Pa-233	Po-213	Pu-246	Rh-105
Nd-149	Pa-234	Po-214	Ra-222	Rh-106
Nd-151	Pa-234m	Po-215	Ra-223	Rh-106m
Ne-19	Pb-195m	Po-216	Ra-224	Rh-107
Ni-56	Pb-198	Po-218	Ra-225	Rh-99
Ni-57	Pb-199	Pr-136	Ra-226	Rh-99m
Ni-59	Pb-200	Pr-137	Ra-227	Rn-218
Ni-63	Pb-201	Pr-138	Ra-228	Rn-219
Ni-65	Pb-202	Pr-138m	Rb-79	Rn-220
Ni-66	Pb-202m	Pr-139	Rb-80	Rn-222
Np-232	Pb-203	Pr-142	Rb-81	Ru-103
Np-233	Pb-205	Pr-142m	Rb-81m	Ru-105
Np-234	Pb-209	Pr-143	Rb-82	Ru-106
Np-235	Pb-210	Pr-144	Rb-82m	Ru-94
Np-236a	Pb-211	Pr-144m	Rb-83	Ru-97
Np-236b	Pb-212	Pr-145	Rb-84	S-35
Np-237	Pb-214	Pr-147	Rb-86	Sb-115
Np-238	Pd-100	Pt-186	Rb-87	Sb-116
Np-239	Pd-101	Pt-188	Rb-88	Sb-116m
Np-240	Pd-103	Pt-189	Rb-89	Sb-117
Np-240m	Pd-107	Pt-191	Re-177	Sb-118m
O-15	Pd-109	Pt-193	Re-178	Sb-119
Os-180	Pm-141	Pt-193m	Re-180	Sb-120a
Os-181	Pm-142	Pt-195m	Re-181	Sb-120b
Os-182	Pm-143	Pt-197	Re-182a	Sb-122

Table A-1 Radionuclides to be Considered in the PA Process (ICRP 1983)

Sb-124	Sn-110	Ta-186	Te-131	U-231
Sb-124m	Sn-111	Tb-147	Te-131m	U-232
Sb-124n	Sn-113	Tb-149	Te-132	U-233
Sb-125	Sn-117m	Tb-150	Te-133	U-234
Sb-126	Sn-119m	Tb-151	Te-133m	U-235
Sb-126m	Sn-121	Tb-153	Te-134	U-236
Sb-127	Sn-121m	Tb-154	Th-226	U-237
Sb-128a	Sn-123	Tb-155	Th-227	U-238
Sb-128b	Sn-123m	Tb-156m	Th-228	U-239
Sb-129	Sn-125	Tb-156n	Th-229	U-240
Sb-130	Sn-126	Tb-157	Th-230	V-47
Sb-131	Sn-127	Tb-158	Th-231	V-48
Sc-43	Sn-128	Tb-160	Th-232	V-49
Sc-44	Sr-80	Tb-161	Th-234	W-176
Sc-44m	Sr-81	Tb-156	Ti-44	W-177
Sc-46	Sr-82	Tc-101	Ti-45	W-178
Sc-47	Sr-83	Tc-104	Tl-194	W-179
Sc-48	Sr-85	Tc-93	Tl-194m	W-181
Sc-49	Sr-85m	Tc-93m	Tl-195	W-185
Se-70	Sr-87m	Tc-94	Tl-197	W-187
Se-73	Sr-89	Tc-94m	Tl-198	W-188
Se-73m	Sr-90	Tc-95	Tl-198m	Xe-120
Se-75	Sr-91	Tc-95m	Tl-199	Xe-121
Se-77m	Sr-92	Tc-96	Tl-200	Xe-122
Se-79	Ta-172	Tc-96m	Tl-201	Xe-123
Se-81	Ta-173	Tc-97	Tl-202	Xe-125
Se-81m	Ta-174	Tc-97m	Tl-204	Xe-127
Se-83	Ta-175	Tc-98	Tl-206	Xe-129m
Si-31	Ta-176	Tc-99	Tl-207	Xe-131m
Si-32	Ta-177	Tc-99m	Tl-208	Xe-133
Sm-141	Ta-178a	Te-116	Tl-209	Xe-133m
Sm-141m	Ta-178b	Te-121	Tm-162	Xe-135
Sm-142	Ta-179	Te-121m	Tm-166	Xe-135m
Sm-145	Ta-180	Te-123	Tm-167	Xe-138
Sm-146	Ta-180m	Te-123m	Tm-170	Y-86
Sm-147	Ta-182	Te-125m	Tm-171	Y-86m
Sm-151	Ta-182m	Te-127	Tm-172	Y-87
Sm-153	Ta-183	Te-127m	Tm-173	Y-88
Sm-155	Ta-184	Te-129	Tm-175	Y-90
Sm-156	Ta-185	Te-129m	U-230	Y-90m

Table A-1 Radionuclides to be Considered in the PA Process (ICRP 1983)

Y-91
Y-91m
Y-92
Y-93
Y-94
Y-95
Yb-162
Yb-166
Yb-167
Yb-169
Yb-175
Yb-177
Yb-178
Zn-62
Zn-63
Zn-65
Zn-69
Zn-69m
Zn-71m
Zn-72
Zr-86
Zr-88
Zr-89
Zr-93
Zr-95
Zr-97

Table A-2 Radionuclides Remaining after Groundwater Screening (Taylor and Collard 2005)

Ag-108m	Ni-59
Al-26	Np-236a
Am-237	Np-237
Am-241	Pa-230
Am-243	Pa-231
Be-10	Pb-202
Bi-210m	Pb-205
Bk-247	Pd-107
Bk-249	Pt-193
C-14	Pu-237
Ca-41	Pu-238
Cd-113	Pu-239
Cf-249	Pu-240
Cf-251	Pu-241
Cf-252	Pu-242
Cl-36	Pu-244
Cm-241	Ra-226
Cm-242	Rb-87
Cm-244	Re-186m
Cm-245	Re-187
Cm-246	Ru-97
Cm-247	Se-79
Cm-248	Si-32
Cm-250	Sm-146
Cs-135	Sm-147
Es-253	Sn-126
Fe-60	Sr-90
Gd-152	Ta-180
Ge-68	Tc-97
H-3	Tc-98
Hf-182	Tc-99
Hg-194	Te-123
Ho-166m	Th-229
I-129	Th-230
In-115	Th-232
Ir-192m	Ti-44
K-40	U-233
La-137	U-234
La-138	U-235
Lu-176	U-236
Mn-53	U-238
Mo-93	V-49
Nb-94	Zr-93

Table A-3 35 Parent Radionuclides to be Considered in E-Area PA Groundwater Analysis (Cook 2006)

Am-241
Am-243
C-14
Cl-36
Cm-244
Cm-245
Cm-247
Cm-248
H-3
I-129
K-40
Mo-93
Nb-94
Ni-59
Np-237
Pd-107
Pu-238
Pu-239
Pu-240
Pu-241
Pu-242
Pu-244
Ra-226
Se-79
Sn-126
Sr-90
Tc-99
Th-230
Th-232
U-233
U-234
U-235
U-236
U-238
Zr-93

Table A-4 Radionuclides Remaining after Atmospheric Screening (Crapse and Cook 2006)

C-14
Cl-36
H-3
I-129
S-35
Sb-124
Sb-125
Se-75
Se-79
Sn-113
Sn-119m
Sn-121
Sn-121m
Sn-123
Sn-126

Table A-5 Radionuclides to be Considered in the Intruder Analysis (Koffman 2004)

Ac-227
Ag-108m
Al-26
Am-241
Am-242m
Am-243
Ar-39
Ba-133
Bi-207
Bk-249
C-14
Ca-41
Cd-113m
Cf-249
Cf-250
Cf-251
Cf-252
Cl-36
Cm-242
Cm-243
Cm-244
Cm-245
Cm-246
Cm-247
Cm-248
Co-60
Cs-134
Cs-135
Cs-137
Eu-152
Eu-154
Eu-155
H-3
I-129
K-40
Kr-85
Mo-93
Na-22
Nb-93m
Nb-94
Ni-59
Ni-63
Np-237
Pa-231
Pb-210
Pd-107
Pu-238
Pu-239
Pu-240
Pu-241
Pu-242
Pu-244
Ra-226
Ra-228
Rb-87
S-35
Sb-125
Sc-46
Se-79
Sm-151
Sn-121m
Sn-126
Sr-90
Tc-99
Th-228
Th-229
Th-230
Th-232
U-232
U-233
U-234
U-235
U-236
U-238
W-181
W-185
W-188
Zr-93

Table A-6 Groundwater Concentration Limits (pCi/L) (EPA 2002 and Eckerman 1988)

Radionuclide	Primary Decay Mode	Secondary Decay Mode
Ac-225	15	
Ac-227	3.9E-01	15
Ac-228	2.5E+03	
Ag-108		
Ag-108m	7.2E+02	
Al-26	3.8E+02	
Am-237	8.3E+04	
Am-241	15	
Am-243	15	
Am-245	3.0E+04	
Am-246m	5.8E+04	
At-217	15	
At-218	15	
Au-194	2.9E+03	
Be-10	1.2E+03	
Bi-210	8.6E+02	
Bi-210m	15	
Bi-211	15	
Bi-212	5.2E+03	15
Bi-213	7.6E+03	15
Bi-214	1.9E+04	
Bk-247	15	
Bk-249	2000	
Bk-250	9.4E+03	
C-14	2000	
Ca-41	4.3E+03	
Cd-113	3.2E+01	
Cf-249	15	
Cf-250	15	
Cf-251	15	
Cf-252	15	
Cl-36	700	
Cm-241	1.2E+03	
Cm-242	15	
Cm-244	15	
Cm-245	15	
Cm-246	15	
Cm-247	15	
Cm-248	15	
Cm-250	7.1E-02	15
Co-60	100	

Table A-6 Groundwater Concentration Limits (pCi/L) (EPA 2002 and Eckerman 1988)

Radionuclide	Primary Decay Mode	Secondary Decay Mode
Co-60m	1.5E+06	
Cs-135	900	
Es-253	15	
Fe-60	3.6E+01	
Fr-221	15	
Fr-223	6.4E+02	
Ga-68	1.6E+04	
Gd-152	15	
Ge-68	5.1E+03	
H-3	20000	
Hf-182	3.5E+02	
Hg-194	8.9E+02	
Ho-166m	6.8E+02	
I-129	1	
In-115	300	
Ir-192	100	
Ir-192m	3.5E+03	
K-40	3.0E+02	
La-137	1.2E+04	
La-138	9.3E+02	
Lu-176	7.5E+02	
Mn-53	5.1E+04	
Mo-93	4.1E+03	
Nb-93m	1000	
Nb-94	7.7E+02	
Ni-59	300	
Np-233	7.4E+05	
Np-236a	6.3E+00	
Np-237	15	
Np-239	300	
Np-240m		
P-32	30	
Pa-230	600	15
Pa-231	15	
Pa-233	300	
Pa-234	2.5E+03	
Pa-234m		
Pb-202	1.4E+02	
Pb-205	3.4E+03	
Pb-209	2.6E+04	
Pb-210	1.0E+00	
Pb-211	1.0E+04	

Table A-6 Groundwater Concentration Limits (pCi/L) (EPA 2002 and Eckerman 1988)

Radionuclide	Primary Decay Mode	Secondary Decay Mode
Pb-212	1.2E+02	
Pb-214	8.8E+03	
Pd-107	3.7E+04	
Po-210	15	
Po-211	15	
Po-212	15	
Po-213	15	
Po-214	15	
Po-215	15	
Po-216	15	
Po-218	15	
Pt-193	3000	
Pu-236	15	
Pu-237	1.2E+04	
Pu-238	15	
Pu-239	15	
Pu-240	15	
Pu-241	300	
Pu-242	15	
Pu-243	1.6E+04	
Pu-244	15	
Pu-246	4.0E+02	
Ra-222	15	
Ra-223	15	
Ra-224	15	
Ra-225	1.4E+01	
Ra-226	15	
Ra-228	3.8E+00	
Rb-87	300	
Re-186	300	
Re-186m	1.4E+03	
Re-187	9000	
Rn-218	15	
Rn-219	15	
Rn-220	15	
Rn-222	15	
Ru-97	1000	
Sb-126	5.1E+02	
Sb-126m	5.8E+04	
Sc-44	3.8E+03	
Se-79	6.3E+02	
Si-32	2.5E+03	

Table A-6 Groundwater Concentration Limits (pCi/L) (EPA 2002 and Eckerman 1988)

Radionuclide	Primary Decay Mode	Secondary Decay Mode
Sm-146	15	
Sm-147	15	
Sn-126	2.8E+02	
Sr-90	8	
Ta-180	1.5E+03	
Ta-182	100	
Tc-97	3.2E+04	
Tc-97m	4.4E+03	
Tc-98	1.1E+03	
Tc-99	900	
Te-123	1.3E+03	
Th-226	15	
Th-227	15	
Th-228	15	
Th-229	15	
Th-230	15	
Th-231	4.1E+03	
Th-232	15	
Th-234	4.0E+02	
Ti-44	2.4E+02	
Tl-202	300	
Tl-206		
Tl-207		
Tl-208		
Tl-209		
U-230	8.2E+11 (30μg/L)	
U-232	6.7E+08 (30μg/L)	
U-233	2.9E+05 (30μg/L)	
U-234	1.9E+05 (30μg/L)	
U-235	6.5E+01 (30μg/L)	
U-236	1.9E+03 (30μg/L)	
U-237	2.4E+12 (30μg/L)	
U-238	1.0E+01 (30μg/L)	
U-240	2.8E+13 (30μg/L)	
V-49	8.9E+04	
Y-90	60	
Zr-93	2000	

Table A-7 Radionuclide Half Life and Branching Data (Tuli 2005)

Parent Radionuclide	Half Life (years)	Daughter1	Branch1	Daughter2	Branch2	Daughter3	Branch3
Ac-225	2.7400E-02	Fr-221	1				
Ac-227	2.1772E+01	Th-227	0.9862	Fr-223	0.0138		
Ac-228	7.0100E-04	Th-228	1				
Ag-108	4.5000E-06						
Ag-108m	4.3800E+02	Ag-108	0.087				
Al-26	7.1700E+05						
Am-237	1.3900E-04	Pu-237	0.9998	Np-233	0.0003		
Am-241	4.3220E+02	Np-237	1				
Am-243	7.3700E+03	Np-239	1				
Am-245	2.3400E-04	Cm-245	1				
Am-246m	4.7600E-05	Cm-246	1				
At-217	1.0200E-09	Bi-213	1				
At-218	4.7600E-08	Bi-214	1				
Au-194	4.3400E-03						
Be-10	1.5100E+06						
Bi-210	1.3700E-02	Po-210	1				
Bi-210m	3.0400E+06	Tl-206	1				
Bi-211	4.0600E-06	Tl-207	0.9972	Po-211	0.0028		
Bi-212	1.1500E-04	Po-212	0.6406	Tl-208	0.3594		
Bi-213	8.6900E-05	Po-213	0.9791	Tl-209	0.0209		
Bi-214	3.7700E-05	Po-214	0.9998				
Bk-247	1.3800E+03	Am-243	1				
Bk-249	9.0400E-01	Cf-249	1	Am-245	0.000014		
Bk-250	3.6800E-04	Cf-250	1				
C-14	5.7300E+03						
Ca-41	1.0200E+05						
Cd-113	7.7100E+15						
Cf-249	3.5200E+02	Cm-245	1				
Cf-250	1.3100E+01	Cm-246	0.9992				
Cf-251	8.9700E+02	Cm-247	1				
Cf-252	2.6500E+00	Cm-248	0.9691				
Cl-36	3.0100E+05						
Cm-241	8.9700E-02	Am-241	0.99	Pu-237	0.01		
Cm-242	4.4700E-01	Pu-238	1				
Cm-244	1.8100E+01	Pu-240	1				
Cm-245	8.5000E+03	Pu-241	1				
Cm-246	4.7600E+03	Pu-242	0.9997				
Cm-247	1.5600E+07	Pu-243	1				
Cm-248	3.4900E+05	Pu-244	0.9161				
Cm-250	8.3100E+03	Pu-246	0.18	Bk-250	0.08		
Co-60	5.2600E+00						

Table A-7 Radionuclide Half Life and Branching Data (Tuli 2005)

Parent Radionuclide	Half Life (years)	Daughter1	Branch1	Daughter2	Branch2	Daughter3	Branch3
Co-60m	1.9900E-05	Co-60	0.9976				
Cs-135	2.3000E+06						
Es-253	5.6100E-02	Bk-249	1				
Fe-60	1.5000E+06	Co-60m	1				
Fr-221	9.3200E-06	At-217	1				
Fr-223	4.1900E-05	Ra-223	1				
Ga-68	1.2900E-04						
Gd-152	1.0800E+14						
Ge-68	7.4200E-01	Ga-68	1				
H-3	1.2320E+01						
Hf-182	8.9100E+06	Ta-182	1				
Hg-194	4.4400E+02	Au-194	1				
Ho-166m	1.2000E+03						
I-129	1.5700E+07						
In-115	4.4100E+14						
Ir-192	2.0200E-01						
Ir-192m	2.4100E+02	Ir-192	1				
K-40	1.2500E+09						
La-137	5.9900E+04						
La-138	1.0200E+11						
Lu-176	3.7700E+10						
Mn-53	3.7400E+06						
Mo-93	4.0000E+03	Nb-93m	1				
Nb-93m	1.6100E+01						
Nb-94	2.0300E+04						
Ni-59	7.6100E+04						
Np-233	6.8800E-05	U-233	1				
Np-236a	1.5400E+05	U-236	0.873	Pu-236	0.125		
Np-237	2.1500E+06	Pa-233	1				
Np-239	6.4700E-03	Pu-239	1				
Np-240m	1.3700E-05	Pu-240	1				
P-32	3.9000E-02						
Pa-230	4.7600E-02	Th-230	0.916	U-230	0.084		
Pa-231	3.2700E+04	Ac-227	1				
Pa-233	7.3900E-02	U-233	1				
Pa-234	7.6400E-04	U-234	1				
Pa-234m	2.2300E-06	U-234	0.9984	Pa-234	0.0016		
Pb-202	5.2600E+04	Tl-202	1				
Pb-205	1.7300E+07						
Pb-209	3.7100E-04						
Pb-210	2.2200E+01	Bi-210	1				
Pb-211	6.8800E-05	Bi-211	1				

Table A-7 Radionuclide Half Life and Branching Data (Tuli 2005)

Parent Radionuclide	Half Life (years)	Daughter1	Branch1	Daughter2	Branch2	Daughter3	Branch3
Pb-212	1.2100E-03	Bi-212	1				
Pb-214	5.1100E-05	Bi-214	1				
Pd-107	6.5000E+06						
Po-210	3.8100E-01						
Po-211	1.6400E-08						
Po-212	9.4800E-15*						
Po-213	1.1600E-13	Pb-209	1				
Po-214	5.2000E-12	Pb-210	1				
Po-215	5.6400E-11	Pb-211	1				
Po-216	4.6000E-09	Pb-212	1				
Po-218	5.9000E-06	Pb-214	0.9998	At-218	0.0002		
Pt-193	5.0100E+01						
Pu-236	2.8600E+00	U-232	1				
Pu-237	1.2400E-01	Np-237	1	U-233	0.000042		
Pu-238	8.7800E+01	U-234	1				
Pu-239	2.4100E+04	U-235	1				
Pu-240	6.5600E+03	U-236	1				
Pu-241	1.4300E+01	Am-241	1	U-237	0.000025		
Pu-242	3.7400E+05	U-238	1				
Pu-243	5.6400E-04	Am-243	1				
Pu-244	7.9900E+07	U-240	0.9988				
Pu-246	2.9700E-02	Am-246m	1				
Ra-222	1.2000E-06	Rn-218	1				
Ra-223	3.1300E-02	Rn-219	1				
Ra-224	9.9600E-03	Rn-220	1				
Ra-225	4.0900E-02	Ac-225	1				
Ra-226	1.6000E+03	Rn-222	1				
Ra-228	5.7400E+00	Ac-228	1				
Rb-87	4.9800E+10						
Re-186	1.0200E-02						
Re-186m	2.0000E+05	Re-186	1				
Re-187	4.1200E+10						
Rn-218	1.1100E-09	Po-214	1				
Rn-219	1.2600E-07	Po-215	1				
Rn-220	1.7600E-06	Po-216	1				
Rn-222	1.0500E-02	Po-218	1				
Ru-97	7.6400E-03	Tc-97	1				
Sb-126	3.3900E-02						
Sb-126m	3.6500E-05	Sb-126	1				
Sc-44	4.5300E-04						
Se-79	2.9500E+05						
Si-32	1.3200E+02	P-32	1				

Table A-7 Radionuclide Half Life and Branching Data (Tuli 2005)

Parent Radionuclide	Half Life (years)	Daughter1	Branch1	Daughter2	Branch2	Daughter3	Branch3
Sm-146	1.0300E+08						
Sm-147	1.0600E+11						
Sn-126	2.3000E+05	Sb-126m	1				
Sr-90	2.8900E+01	Y-90	1				
Ta-180	1.2000E+15						
Ta-182	3.1400E-01						
Tc-97	4.2100E+06						
Tc-97m	2.5100E-01	Tc-97	1				
Tc-98	4.2000E+06						
Tc-99	2.1110E+05						
Te-123	9.2000E+16						
Th-226	5.8000E-05	Ra-222	1				
Th-227	5.1100E-02	Ra-223	1				
Th-228	1.9100E+00	Ra-224	1				
Th-229	7.3600E+03	Ra-225	1				
Th-230	7.5500E+04	Ra-226	1				
Th-231	2.9100E-03	Pa-231	1				
Th-232	1.4050E+10	Ra-228	1				
Th-234	6.6000E-02	Pa-234m	1				
Ti-44	6.0000E+01	Sc-44	1				
Tl-202	3.3600E-02						
Tl-206	7.9900E-06						
Tl-207	9.0700E-06						
Tl-208	5.8000E-06						
Tl-209	4.1200E-06	Pb-209	1				
U-230	5.7100E-02	Th-226	1				
U-232	6.8900E+01	Th-228	1				
U-233	1.5920E+05	Th-229	1				
U-234	2.4550E+05	Th-230	1				
U-235	7.0400E+08	Th-231	1				
U-236	2.3420E+07	Th-232	1				
U-237	1.8500E-02	Np-237	1				
U-238	4.4680E+09	Th-234	1				
U-240	1.6100E-03	Np-240m	1				
V-49	9.0100E-01						
Y-90	7.3200E-03						
Zr-93	1.5300E+06	Nb-93m	1				

* Half life of Po-212 from Radionuclide Transformations: Energy and Intensity of Emissions. International Commission on Radiological Protection Report 38. Pergamon Press, Oxford. 1983.

Table A-8 Radionuclide Decay Modes (Tuli 2005)

	Decay Mode (percentage if dual mode)	
Nuclide	Non-Alpha	Alpha
Ac-225		X
Ac-227	99	1
Ac-228	X	
Ag-108	X	
Ag-108m	X	
Al-26	X	
Am-237	X	
Am-241		X
Am-243		X
Am-245	X	
Am-246m	X	
At-217		X
At-218		X
Au-194	X	
Be-10	X	
Bi-210	X	
Bi-210m		X
Bi-211		X
Bi-212	64	36
Bi-213	98	2
Bi-214	X	
Bk-247		X
Bk-249	X	
Bk-250	X	
C-14	X	
Ca-41	X	
Cd-113	X	
Cf-249		X
Cf-250		X
Cf-251		X
Cf-252[1]		97
Cl-36	X	
Cm-241	99	1
Cm-242		X
Cm-244		X
Cm-245		X
Cm-246		X
Cm-247		X
Cm-248[1]		92

Table A-8 Radionuclide Decay Modes (Tuli 2005)

	Decay Mode (percentage if dual mode)	
Nuclide	Non-Alpha	Alpha
Cm-250[1]	8	18
Co-60	X	
Co-60m	X	
Cs-135	X	
Es-253		X
Fe-60	X	
Fr-221		X
Fr-223	X	
Ga-68	X	
Gd-152		X
Ge-68	X	
H-3	X	
Hf-182	X	
Hg-194	X	
Ho-166m	X	
I-129	X	
In-115	X	
Ir-192	X	
Ir-192m	X	
K-40	X	
La-137	X	
La-138	X	
Lu-176	X	
Mn-53	X	
Mo-93	X	
Nb-93m	X	
Nb-94	X	
Ni-59	X	
Np-233	X	
Np-236a	X	
Np-237		X
Np-239	X	
Np-240m	X	
P-32	X	
Pa-230	X	
Pa-231		X
Pa-233	X	
Pa-234	X	
Pa-234m	X	
Pb-202	X	

Table A-8 Radionuclide Decay Modes (Tuli 2005)

	Decay Mode (percentage if dual mode)	
Nuclide	Non-Alpha	Alpha
Pb-205	X	
Pb-209	X	
Pb-210	X	
Pb-211	X	
Pb-212	X	
Pb-214	X	
Pd-107	X	
Po-210		X
Po-211		X
Po-212[2]		X
Po-213		X
Po-214		X
Po-215		X
Po-216		X
Po-218		X
Pt-193	X	
Pu-236		X
Pu-237	X	
Pu-238		X
Pu-239		X
Pu-240		X
Pu-241	X	
Pu-242		X
Pu-243	X	
Pu-244		X
Pu-246	X	
Ra-222		X
Ra-223		X
Ra-224		X
Ra-225	X	
Ra-226		X
Ra-228	X	
Rb-87	X	
Re-186	X	
Re-186m	X	
Re-187	X	
Rn-218		X
Rn-219		X
Rn-220		X
Rn-222		X

Table A-8 Radionuclide Decay Modes (Tuli 2005)

	Decay Mode (percentage if dual mode)	
Nuclide	Non-Alpha	Alpha
Ru-97	X	
Sb-126	X	
Sb-126m	X	
Sc-44	X	
Se-79	X	
Si-32	X	
Sm-146		X
Sm-147		X
Sn-126	X	
Sr-90	X	
Ta-180	X	
Ta-182	X	
Tc-97	X	
Tc-97m	X	
Tc-98	X	
Tc-99	X	
Te-123	X	
Th-226		X
Th-227		X
Th-228		X
Th-229		X
Th-230		X
Th-231	X	
Th-232		X
Th-234	X	
Ti-44	X	
Tl-202	X	
Tl-206	X	
Tl-207	X	
Tl-208	X	
Tl-209	X	
U-230		X
U-232		X
U-233		X
U-234		X
U-235		X
U-236		X
U-237	X	
U-238		X
U-240	X	

Table A-8 Radionuclide Decay Modes (Tuli 2005)

	Decay Mode (percentage if dual mode)	
Nuclide	Non-Alpha	Alpha
V-49	X	
Y-90	X	
Zr-93	X	

[1] The percentage of decays not accounted for in this table for Cf-252, Cm-248 and Cm-250 are due to spontaneous fission, which is not specifically accounted for in this PA.

[2] Decay mode for Po-212 from Radionuclide Transformations: Energy and Intensity of Emissions. International Commission on Radiological Protection Report 38. Pergamon Press, Oxford, 1983.

Table A-9 Ingestion Effective Dose Conversion Factors (Eckerman et al. 1988)

Radionuclide	Sv/Bq	mrem/pCi	rem/uCi	Gastrointestinal Absorption Factor (f1), if more than one is used from Eckerman 1988[1]
Ac-225	3.00E-08	1.11E-04	1.11E-01	
Ac-227	3.80E-06	1.41E-02	1.41E+01	
Ac-228	5.85E-10	2.16E-06	2.16E-03	
Ag-108	0.00E+00	0.00E+00	0.00E+00	
Ag-108m	2.06E-09	7.62E-06	7.62E-03	
Al-26	3.94E-09	1.46E-05	1.46E-02	
Am-237	1.78E-11	6.59E-08	6.59E-05	
Am-241	9.84E-07	3.64E-03	3.64E+00	
Am-243	9.79E-07	3.62E-03	3.62E+00	
Am-245	4.88E-11	1.81E-07	1.81E-04	
Am-246m	2.54E-11	9.40E-08	9.40E-05	
At-217	0.00E+00	0.00E+00	0.00E+00	
At-218	0.00E+00	0.00E+00	0.00E+00	
Au-194	5.08E-10	1.88E-06	1.88E-03	
Be-10	1.26E-09	4.66E-06	4.66E-03	
Bi-210	1.73E-09	6.40E-06	6.40E-03	
Bi-210m	2.59E-08	9.58E-05	9.58E-02	
Bi-211	0.00E+00	0.00E+00	0.00E+00	
Bi-212	2.87E-10	1.06E-06	1.06E-03	
Bi-213	1.95E-10	7.22E-07	7.22E-04	
Bi-214	7.64E-11	2.83E-07	2.83E-04	
Bk-247	1.27E-06	4.70E-03	4.70E+00	
Bk-249	3.24E-09	1.20E-05	1.20E-02	
Bk-250	1.57E-10	5.81E-07	5.81E-04	
C-14	5.64E-10	2.09E-06	2.09E-03	
Ca-41	3.44E-10	1.27E-06	1.27E-03	
Cd-113	4.70E-08	1.74E-04	1.74E-01	
Cf-249	1.28E-06	4.74E-03	4.74E+00	
Cf-250	5.76E-07	2.13E-03	2.13E+00	
Cf-251	1.31E-06	4.85E-03	4.85E+00	
Cf-252	2.93E-07	1.08E-03	1.08E+00	
Cl-36	8.18E-10	3.03E-06	3.03E-03	
Cm-241	1.21E-09	4.48E-06	4.48E-03	
Cm-242	3.10E-08	1.15E-04	1.15E-01	
Cm-244	5.45E-07	2.02E-03	2.02E+00	

Table A-9 Ingestion Effective Dose Conversion Factors (Eckerman et al. 1988)

Radionuclide	Sv/Bq	mrem/pCi	rem/uCi	Gastrointestinal Absorption Factor (f1), if more than one is used from Eckerman 1988[1]
Cm-245	1.01E-06	3.74E-03	3.74E+00	
Cm-246	1.00E-06	3.70E-03	3.70E+00	
Cm-247	9.24E-07	3.42E-03	3.42E+00	
Cm-248	3.68E-06	1.36E-02	1.36E+01	
Cm-250	2.10E-05	7.77E-02	7.77E+01	
Co-60	7.28E-09	2.69E-05	2.69E-02	f1=3E-1
Co-60	2.77E-09	1.02E-05	1.02E-02	f1=5E-2
Co-60m	9.82E-13	3.63E-09	3.63E-06	f1=3E-1
Co-60m	9.70E-13	3.59E-09	3.59E-06	f1=5E-2
Cs-135	1.91E-09	7.07E-06	7.07E-03	
Es-253	9.10E-09	3.37E-05	3.37E-02	
Fe-60	4.12E-08	1.52E-04	1.52E-01	
Fr-221	0.00E+00	0.00E+00	0.00E+00	
Fr-223	2.33E-09	8.62E-06	8.62E-03	
Ga-68	9.24E-11	3.42E-07	3.42E-04	
Gd-152	4.34E-08	1.61E-04	1.61E-01	
Ge-68	2.89E-10	1.07E-06	1.07E-03	
H-3	1.73E-11	6.40E-08	6.40E-05	
Hf-182	4.29E-09	1.59E-05	1.59E-02	
Hg-194	7.78E-08	2.88E-04	2.88E-01	f1=1.0
Hg-194	1.66E-09	6.14E-06	6.14E-03	f1=2E-2
Ho-166m	2.18E-09	8.07E-06	8.07E-03	
I-129	7.46E-08	2.76E-04	2.76E-01	
In-115	4.26E-08	1.58E-04	1.58E-01	
Ir-192	1.55E-09	5.74E-06	5.74E-03	
Ir-192m	4.23E-10	1.57E-06	1.57E-03	
K-40	5.02E-09	1.86E-05	1.86E-02	
La-137	1.23E-10	4.55E-07	4.55E-04	
La-138	1.59E-09	5.88E-06	5.88E-03	
Lu-176	1.98E-09	7.33E-06	7.33E-03	
Mn-53	2.92E-11	1.08E-07	1.08E-04	
Mo-93	3.64E-10	1.35E-06	1.35E-03	f1=8E-1
Nb-93m	1.41E-10	5.22E-07	5.22E-04	
Nb-94	1.93E-09	7.14E-06	7.14E-03	
Ni-59	5.67E-11	2.10E-07	2.10E-04	
Np-233	1.99E-12	7.36E-09	7.36E-06	

Table A-9 Ingestion Effective Dose Conversion Factors (Eckerman et al. 1988)

Radionuclide	Sv/Bq	mrem/pCi	rem/uCi	Gastrointestinal Absorption Factor (f1), if more than one is used from Eckerman 1988[1]
Np-236a	2.34E-07	8.66E-04	8.66E-01	
Np-237	1.20E-06	4.44E-03	4.44E+00	
Np-239	8.82E-10	3.26E-06	3.26E-03	
Np-240m	0.00E+00	0.00E+00	0.00E+00	
P-32	2.37E-09	8.77E-06	8.77E-03	
Pa-230	1.68E-09	6.22E-06	6.22E-03	
Pa-231	2.86E-06	1.06E-02	1.06E+01	
Pa-233	9.81E-10	3.63E-06	3.63E-03	
Pa-234	5.84E-10	2.16E-06	2.16E-03	
Pa-234m	0.00E+00	0.00E+00	0.00E+00	
Pb-202	1.05E-08	3.89E-05	3.89E-02	
Pb-205	4.41E-10	1.63E-06	1.63E-03	
Pb-209	5.75E-11	2.13E-07	2.13E-04	
Pb-210	1.45E-06	5.37E-03	5.37E+00	
Pb-211	1.42E-10	5.25E-07	5.25E-04	
Pb-212	1.23E-08	4.55E-05	4.55E-02	
Pb-214	1.69E-10	6.25E-07	6.25E-04	
Pd-107	4.04E-11	1.49E-07	1.49E-04	
Po-210	5.14E-07	1.90E-03	1.90E+00	
Po-211	0.00E+00	0.00E+00	0.00E+00	
Po-212	0.00E+00	0.00E+00	0.00E+00	
Po-213	0.00E+00	0.00E+00	0.00E+00	
Po-214	0.00E+00	0.00E+00	0.00E+00	
Po-215	0.00E+00	0.00E+00	0.00E+00	
Po-216	0.00E+00	0.00E+00	0.00E+00	
Po-218	0.00E+00	0.00E+00	0.00E+00	
Pt-193	3.21E-11	1.19E-07	1.19E-04	
Pu-236	3.15E-07	1.17E-03	1.17E+00	f1=1E-3
Pu-237	1.20E-10	4.44E-07	4.44E-04	f1=1E-3
Pu-238	8.65E-07	3.20E-03	3.20E+00	f1=1E-3
Pu-239	9.56E-07	3.54E-03	3.54E+00	f1=1E-3
Pu-240	9.56E-07	3.54E-03	3.54E+00	f1=1E-3
Pu-241	1.85E-08	6.85E-05	6.85E-02	f1=1E-3
Pu-242	9.08E-07	3.36E-03	3.36E+00	f1=1E-3
Pu-243	9.02E-11	3.34E-07	3.34E-04	f1=1E-3
Pu-244	8.97E-07	3.32E-03	3.32E+00	f1=1E-3

Table A-9 Ingestion Effective Dose Conversion Factors (Eckerman et al. 1988)

Radionuclide	Sv/Bq	mrem/pCi	rem/uCi	Gastrointestinal Absorption Factor (f1), if more than one is used from Eckerman 1988[1]
Pu-246	3.66E-09	1.35E-05	1.35E-02	
Ra-222	0.00E+00	0.00E+00	0.00E+00	
Ra-223	1.78E-07	6.59E-04	6.59E-01	
Ra-224	9.89E-08	3.66E-04	3.66E-01	
Ra-225	1.04E-07	3.85E-04	3.85E-01	
Ra-226	3.58E-07	1.32E-03	1.32E+00	
Ra-228	3.88E-07	1.44E-03	1.44E+00	
Rb-87	1.33E-09	4.92E-06	4.92E-03	
Re-186	7.95E-10	2.94E-06	2.94E-03	
Re-186m	1.08E-09	4.00E-06	4.00E-03	
Re-187	2.57E-12	9.51E-09	9.51E-06	
Rn-218	0.00E+00	0.00E+00	0.00E+00	
Rn-219	0.00E+00	0.00E+00	0.00E+00	
Rn-220	0.00E+00	0.00E+00	0.00E+00	
Rn-222	0.00E+00	0.00E+00	0.00E+00	
Ru-97	1.88E-10	6.96E-07	6.96E-04	
Sb-126	2.76E-09	1.02E-05	1.02E-02	f1=1E-1
Sb-126	2.89E-09	1.07E-05	1.07E-02	f1=1E-2
Sb-126m	2.53E-11	9.36E-08	9.36E-05	f1=1E-1
Sb-126m	2.54E-11	9.40E-08	9.40E-05	f1=1E-2
Sc-44	3.87E-10	1.43E-06	1.43E-03	
Se-79	2.35E-09	8.70E-06	8.70E-03	f1=8E-1
Si-32	5.90E-10	2.18E-06	2.18E-03	
Sm-146	5.51E-08	2.04E-04	2.04E-01	
Sm-147	5.01E-08	1.85E-04	1.85E-01	
Sn-126	5.27E-09	1.95E-05	1.95E-02	
Sr-90	3.85E-08	1.42E-04	1.42E-01	f1=3E-1
Ta-180	9.82E-10	3.63E-06	3.63E-03	
Ta-182	1.76E-09	6.51E-06	6.51E-03	
Tc-97	4.63E-11	1.71E-07	1.71E-04	
Tc-97m	3.36E-10	1.24E-06	1.24E-03	
Tc-98	1.32E-09	4.88E-06	4.88E-03	
Tc-99	3.95E-10	1.46E-06	1.46E-03	
Te-123	1.13E-09	4.18E-06	4.18E-03	
Th-226	2.50E-10	9.25E-07	9.25E-04	
Th-227	1.03E-08	3.81E-05	3.81E-02	

Table A-9 Ingestion Effective Dose Conversion Factors (Eckerman et al. 1988)

Radionuclide	Sv/Bq	mrem/pCi	rem/uCi	Gastrointestinal Absorption Factor (f1), if more than one is used from Eckerman 1988[1]
Th-228	1.07E-07	3.96E-04	3.96E-01	
Th-229	9.54E-07	3.53E-03	3.53E+00	
Th-230	1.48E-07	5.48E-04	5.48E-01	
Th-231	3.65E-10	1.35E-06	1.35E-03	
Th-232	7.38E-07	2.73E-03	2.73E+00	
Th-234	3.69E-09	1.37E-05	1.37E-02	
Ti-44	6.25E-09	2.31E-05	2.31E-02	
Tl-202	3.98E-10	1.47E-06	1.47E-03	
Tl-206	0.00E+00	0.00E+00	0.00E+00	
Tl-207	0.00E+00	0.00E+00	0.00E+00	
Tl-208	0.00E+00	0.00E+00	0.00E+00	
Tl-209	0.00E+00	0.00E+00	0.00E+00	
U-230	2.44E-07	9.03E-04	9.03E-01	f1=5E-2
U-232	3.54E-07	1.31E-03	1.31E+00	f1=5E-2
U-233	7.81E-08	2.89E-04	2.89E-01	f1=5E-2
U-234	7.66E-08	2.83E-04	2.83E-01	f1=5E-2
U-235	7.19E-08	2.66E-04	2.66E-01	f1=5E-2
U-236	7.26E-08	2.69E-04	2.69E-01	f1=5E-2
U-237	8.48E-10	3.14E-06	3.14E-03	f1=5E-2
U-238	6.88E-08	2.55E-04	2.55E-01	f1=5E-2
U-240	1.16E-09	4.29E-06	4.29E-03	
V-49	1.66E-11	6.14E-08	6.14E-05	
Y-90	2.91E-09	1.08E-05	1.08E-02	
Zr-93	4.48E-10	1.66E-06	1.66E-03	

[1] In a few cases (Co-60, Co-60m, Hg-194, Sb-126 and Sb-126m), higher f1 values were used for the intruder than for the all pathways analyses.

Table A-10 Radionuclide Decay Constants (1/day) (Tuli 2005)

Radionuclide	Decay Constant	Radionuclide	Decay Constant
Ac-225	6.93E-02	Es-253	3.38E-02
Ac-227	8.72E-05	Fe-60	1.27E-09
Ac-228	2.71E+00	Fr-221	2.04E+02
Ag-108	4.22E+02	Fr-223	4.53E+01
Ag-108m	4.33E-06	Ga-68	1.47E+01
Al-26	2.65E-09	Gd-152	1.76E-17
Am-237	1.37E+01	Ge-68	2.56E-03
Am-241	4.39E-06	H-3	1.54E-04
Am-243	2.57E-07	Hf-182	2.13E-10
Am-245	8.11E+00	Hg-194	4.27E-06
Am-246m	3.99E+01	Ho-166m	1.58E-06
At-217	1.86E+06	I-129	1.21E-10
At-218	3.99E+04	In-115	4.30E-18
Au-194	4.37E-01	Ir-192	9.39E-03
Be-10	1.26E-09	Ir-192m	7.87E-06
Bi-210	1.39E-01	K-40	1.52E-12
Bi-210m	6.24E-10	La-137	3.17E-08
Bi-211	4.67E+02	La-138	1.86E-14
Bi-212	1.65E+01	Lu-176	5.03E-14
Bi-213	2.18E+01	Mn-53	5.07E-10
Bi-214	5.03E+01	Mo-93	4.74E-07
Bk-247	1.38E-06	Nb-93m	1.18E-04
Bk-249	2.10E-03	Nb-94	9.35E-08
Bk-250	5.16E+00	Ni-59	2.49E-08
C-14	3.31E-07	Np-233	2.76E+01
Ca-41	1.86E-08	Np-236a	1.23E-08
Cd-113	2.46E-19	Np-237	8.83E-10
Cf-249	5.39E-06	Np-239	2.93E-01
Cf-250	1.45E-04	Np-240m	1.39E+02
Cf-251	2.12E-06	P-32	4.87E-02
Cf-252	7.16E-04	Pa-230	3.99E-02
Cl-36	6.30E-09	Pa-231	5.80E-08
Cm-241	2.12E-02	Pa-233	2.57E-02
Cm-242	4.25E-03	Pa-234	2.48E+00
Cm-244	1.05E-04	Pa-234m	8.51E+02
Cm-245	2.23E-07	Pb-202	3.61E-08
Cm-246	3.99E-07	Pb-205	1.10E-10
Cm-247	1.22E-10	Pb-209	5.12E+00
Cm-248	5.44E-09	Pb-210	8.55E-05
Cm-250	2.28E-07	Pb-211	2.76E+01
Co-60	3.61E-04	Pb-212	1.57E+00
Co-60m	9.54E+01	Pb-214	3.71E+01
Cs-135	8.25E-10	Pd-107	2.92E-10

Table A-10 Radionuclide Decay Constants (1/day) (Tuli 2005)

Radionuclide	Decay Constant	Radionuclide	Decay Constant
Po-210	4.98E-03	Ta-182	6.04E-03
Po-211	1.16E+05	Tc-97	4.50E-10
Po-212	2.00E+11	Tc-97m	7.56E-03
Po-213	1.64E+10	Tc-98	4.52E-10
Po-214	3.65E+08	Tc-99	8.99E-09
Po-215	3.36E+07	Te-123	2.06E-20
Po-216	4.13E+05	Th-226	3.27E+01
Po-218	3.22E+02	Th-227	3.71E-02
Pt-193	3.79E-05	Th-228	9.94E-04
Pu-236	6.64E-04	Th-229	2.58E-07
Pu-237	1.53E-02	Th-230	2.51E-08
Pu-238	2.16E-05	Th-231	6.52E-01
Pu-239	7.87E-08	Th-232	1.35E-13
Pu-240	2.89E-07	Th-234	2.88E-02
Pu-241	1.33E-04	Ti-44	3.16E-05
Pu-242	5.07E-09	Tl-202	5.65E-02
Pu-243	3.36E+00	Tl-206	2.38E+02
Pu-244	2.38E-11	Tl-207	2.09E+02
Pu-246	6.39E-02	Tl-208	3.27E+02
Ra-222	1.58E+03	Tl-209	4.61E+02
Ra-223	6.06E-02	U-230	3.32E-02
Ra-224	1.91E-01	U-232	2.75E-05
Ra-225	4.64E-02	U-233	1.19E-08
Ra-226	1.19E-06	U-234	7.73E-09
Ra-228	3.31E-04	U-235	2.70E-12
Rb-87	3.81E-14	U-236	8.10E-11
Re-186	1.86E-01	U-237	1.03E-01
Re-186m	9.49E-09	U-238	4.25E-13
Re-187	4.61E-14	U-240	1.18E+00
Rn-218	1.71E+06	V-49	2.11E-03
Rn-219	1.51E+04	Y-90	2.59E-01
Rn-220	1.08E+03	Zr-93	1.24E-09
Rn-222	1.81E-01		
Ru-97	2.48E-01		
Sb-126	5.60E-02		
Sb-126m	5.20E+01		
Sc-44	4.19E+00		
Se-79	6.43E-09		
Si-32	1.44E-05		
Sm-146	1.84E-11		
Sm-147	1.79E-14		
Sn-126	8.25E-09		
Sr-90	6.57E-05		
Ta-180	1.58E-18		

Table A-11 Specific Activities (Taylor 2006)

Radionuclide*	Ci/mole	Ci/g
Ac-227	1.64E+04	7.23E+01
Ag-108m	8.16E+02	7.56E+00
Al-26	4.99E-01	1.92E-02
Am-237	2.57E+09	1.09E+07
Am-241	8.27E+02	3.43E+00
Am-243	4.85E+01	2.00E-01
Be-10	2.37E-01	2.37E-02
Bi-210m	1.18E-01	5.60E-04
Bk-247	2.59E+02	1.05E+00
Bk-249	3.95E+05	1.59E+03
C-14	6.24E+01	4.46E+00
Ca-41	3.50E+00	8.55E-02
Cd-113	4.64E-11	4.10E-13
Cf-249	1.02E+03	4.08E+00
Cf-250	2.73E+04	1.09E+02
Cf-251	3.99E+02	1.59E+00
Cf-252	1.35E+05	5.35E+02
Cl-36	1.19E+00	3.30E-02
Cm-241	3.99E+06	1.65E+04
Cm-242	8.00E+05	3.30E+03
Cm-244	1.98E+04	8.09E+01
Cm-245	4.21E+01	1.72E-01
Cm-246	7.51E+01	3.05E-01
Cm-247	2.29E-02	9.28E-05
Cm-248	1.02E+00	4.13E-03
Cm-250	4.30E+01	1.72E-01
Co-60	6.80E+04	1.13E+03
Cs-135	1.55E-01	1.15E-03
Es-253	6.37E+06	2.52E+04
Fe-60	2.38E-01	3.97E-03
Gd-152	3.31E-09	2.18E-11
Ge-68	4.82E+05	7.09E+03
H-3	2.90E+04	9.67E+03
Hf-182	4.01E-02	2.20E-04
Hg-194	8.05E+02	4.15E+00
Ho-166m	2.98E+02	1.79E+00
I-129	2.28E-02	1.77E-04
In-115	8.11E-10	7.05E-12
Ir-192m	1.48E+03	7.73E+00
K-40	2.86E-04	7.15E-06
La-137	5.97E+00	4.36E-02
La-138	3.50E-06	2.54E-08
Lu-176	9.48E-06	5.39E-08

Table A-11 Specific Activities (Taylor 2006)

Radionuclide*	Ci/mole	Ci/g
Mn-53	9.56E-02	1.80E-03
Mo-93	8.94E+01	9.61E-01
Nb-93m	2.22E+04	2.39E+02
Nb-94	1.76E+01	1.87E-01
Ni-59	4.70E+00	7.96E-02
Np-236a	2.32E+00	9.84E-03
Np-237	1.66E-01	7.02E-04
Pa-230	7.51E+06	3.27E+04
Pa-231	1.09E+01	4.73E-02
Pb-202	6.80E+00	3.36E-02
Pb-205	2.07E-02	1.01E-04
Pb-210	1.61E+04	7.67E+01
Pd-107	5.50E-02	5.14E-04
Pt-193	7.14E+03	3.70E+01
Pu-237	2.88E+06	1.22E+04
Pu-238	4.07E+03	1.71E+01
Pu-239	1.48E+01	6.21E-02
Pu-240	5.45E+01	2.27E-01
Pu-241	2.50E+04	1.04E+02
Pu-242	9.56E-01	3.95E-03
Pu-244	4.47E-03	1.83E-05
Ra-226	2.23E+02	9.89E-01
Ra-228	6.23E+04	2.73E+02
Rb-87	7.18E-06	8.25E-08
Re-186m	1.79E+00	9.61E-03
Re-187	8.68E-06	4.64E-08
Ru-97	4.68E+07	4.82E+05
Se-79	1.21E+00	1.53E-02
Si-32	2.71E+03	8.46E+01
Sm-146	3.47E-03	2.38E-05
Sm-147	3.37E-06	2.29E-08
Sn-126	1.55E+00	1.23E-02
Sr-90	1.24E+04	1.37E+02
Ta-180	2.98E-10	1.66E-12
Tc-97	8.47E-02	8.73E-04
Tc-99	1.69E+00	1.71E-02
Te-123	3.89E-12	3.16E-14
Th-229	4.86E+01	2.12E-01
Th-230	4.74E+00	2.06E-02
Th-232	2.54E-05	1.10E-07
Ti-44	5.96E+03	1.35E+02
U-232	5.19E+03	2.24E+01
U-233	2.25E+00	9.64E-03
U-234	1.46E+00	6.22E-03

Table A-11 Specific Activities (Taylor 2006)

Radionuclide*	Ci/mole	Ci/g
U-235	5.08E-04	2.16E-06
U-236	1.53E-02	6.47E-05
U-238	8.00E-05	3.36E-07
V-49	3.97E+05	8.10E+03
Zr-93	2.34E-01	2.51E-03

* Parents and daughters in groundwater transport calculations with half-lives greater than 5 years.

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