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LLWR Radiological Handbook

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1 Introduction

1.1 Aim and Scope

The aim of the Radiological Handbook is to provide a reference for common radiological data likely to be applicable across a range of different exposure calculations to be undertaken in support of the Environmental Safety Case (ESC) and future iterations of the ESC, and to provide an audit trail demonstrating the provenance of those data. It will provide an important 'Level 3' reference underpinning the data used in a range of models.

The radiological handbook includes the following data:

1. **Radionuclide list**

A list of radionuclides included in the LLWR inventory is presented, together with a simplified list removing those radionuclides with very small inventories and short half lives. The list is then augmented by decay chain progeny radionuclides to provide an overall statement of the radionuclides of interest.

2. **Radionuclide data**

These data include: atomic masses, half lives, decay modes and decay chain data, presented for parent radionuclides with a non-negligible inventory and those progeny that may be explicitly represented in modelling, rather than being treated as present in secular equilibrium.

3. **Committed effective dose per unit intake**

These data include: values of committed effective dose per unit intake by inhalation and ingestion, including summation of short-lived progeny implicitly included with a parent. Notes are provided as to the assumed radionuclide form, aerosol Activity Median Aerodynamic Diameter (AMAD) and other factors that are taken into account.

4. **Effective dose rates for external exposure**

These data include: effective dose rates for photon exposure from a semi-infinite slab and a semi-infinite surface. A method statement and factors are given for calculating effective dose rates for photon exposure from volumetrically and surface contaminated spheres based on the semi-infinite slab and surface values. In addition, values are given for equivalent dose rates at 1m in vacuum from point sources for photon and beta emissions. A method statement is provided for calculating equivalent dose rates at alternative distances and for calculating the equivalent dose rate to the skin.

5. **Common radionuclide-independent exposure data**

These data are for human exposures and include: receptor breathing rates; inadvertent soil and sediment ingestion rates; water intake rates; and airborne dust concentrations. These are 'default values' that may need to be amended for specific PEG and exposure circumstances.

1.2 Data Sources

Data have been selected from internationally recognised sources with a proven pedigree. Specific references are provided for each of the data sets.

Specifically, it is noted that the decay chain characteristics (half lives, branching ratios and emissions) are from ICRP 107 (ICRP, 2008). ICRP 107 supersedes ICRP 38 (1983), but the available internal and external dose factors have not been updated in the international literature. However, the available dose factors are not uniformly consistent with ICRP 38, and so it is considered appropriate to use the updated decay chain characteristics while retaining existing dose factors that have national and international regulatory status (e.g. through inclusion in Basic Safety Standards (BSS) and Federal Guidance Reports).

1.3 Quality Assurance

This handbook represents a compilation of the relevant data and references for the ESC, with appropriate discussions and clarifications regarding the nature of the data and the basis for those data in observations. However, it does not provide any details on uses of the data. It is anticipated that other Level 3 documents will provide the necessary discussion on the use of specific parameter values, or distributions of such values, for particular calculations.

All of the source data come from standard nuclear sources and international radiological reference sources or have been derived during underpinning work for the ESC.

The data presented in the main body of the handbook have been fully checked against the main references. Every value in every table or section has been cross-checked with the original references, and the report has also been subject to overview, rationale and consistency checks with further spot-checking.

2 Radionuclides of Interest

146 radionuclides are present in the inventory of past and predicted future proposals to the LLWR (Serco, 2010)[1]. Of these radionuclides, 66 have short half-lives (<1 y) and do not contribute significantly to the inventory of another disposed radionuclide upon decay[2], or have very low disposed inventories (< 1MBq). Such radionuclides are excluded from further consideration[3].

These exclusion criteria are set very cautiously to ensure that all radionuclides of potential interest are carried forward. Formal screening of the remaining radionuclides for significance to the 2011 ESC will take place at a subsequent assessment step.

The resulting lists of radionuclides are shown below (and listed alphabetically in Appendix A).

- 78 retained disposal inventory radionuclides: H-3, Be-10, C-14, Na-22, Al-26, Cl-36, Ar-39, K-40, Ca-41, Fe-55, Co-60, Ni-59, Ni-63, Se-79, Kr-81, Kr-85, Rb-87, Sr-90, Zr-93, Nb-93m, Nb-94, Mo-93, Tc-99, Ru-106, Ag-108m, Cd-109, Cd-113m, Sn-121m, Sn-126, Sb-125, I-129, Cs-134, Cs-135, Cs-137, Ba-133, La-137, Pm-145, Pm-147, Sm-151, Eu-152, Eu-154, Eu-155, Ho-163, Ho-166m, Hf-178n, Pt-193, Tl-204, Pb-210, Ra-226, Ra-228, Ac-227, Th-228, Th-229, Th-230, Th-232, Pa-231, U-232, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Am-241, Am-242m, Am-243, Cm-243, Cm-244, Cm-245, Cm-246, Cm-248, Cf-250, Cf-251.

- 68 excluded radionuclides: P-33, S-35, Ar-42, Ca-45, Sc-46, Cr-51, Mn-53, Mn-54, Fe-59, Co-57, Co-58, Zn-65, Se-75, Rb-86, Sr-85, Sr-89, Y-90, Y-91, Zr-95, Nb-91, Nb-92, Nb-95, Tc-97, Ru-103, Pd-107, Ag-110m, Sn-113, Sn-119m, Sn-123, Sb-124, Sb-126, Te-125m, Te-127m, Te-129m, I-125, I-131, Cs-136, Ba-140, La-138, Ce-141, Ce-144, Pr-143, Sm-147, Es-254, Gd-153, Tm-170, Tm-171, Lu-174, Lu-176, Hf-182, Ta-182, W-181, Ir-192, Hg-203, Th-234, Pb-205, Bi-208, Bi-210m, Po-210, Ra-223, Ra-225, Th-227, Pa-232, Pa-233, Pu-236, Cm-242, Cf-249, Cf-252.

Data also needs to be presented for radionuclides present within decay chains associated with the 78 retained radionuclides. Those radionuclides that can be considered to be in secular equilibrium with the parent were identified and intermediate radionuclides were excluded from explicit consideration if the ratio of the decay constant to that of its parent is greater than 1,000, unless the half-life of the intermediate radionuclide is greater than one year.

The simplified decay chains that result are the result of the application of these criteria are given in Section 3. The following list presents all the radionuclides that are

[1] List compiled from Trench, Vault 8 and Future Vault inventory estimates, using Inventory Case 2 for future disposals.

[2] That is they decay directly to stable products, or their inventories are less than 0.1% of the disposed inventory of the next decay chain daughter with a half-life of > 1y.

[3] A further two radionuclides (Cf-252 and Pu-236) are excluded on the basis that their half lives are close to the 1 y short half life criterion (both < 3 y), and their short half lives plus the ratio of their inventories to that of their daughters means that decay of the parent will have an insignificant contribution to the mass of the daughter.

of interest once progeny from the simplified decay chains are added to the list of retained disposal radionuclides.

83 radionuclides of interest: H-3, Be-10, C-14, Na-22, Al-26, Cl-36, Ar-39, K-40, Ca-41, Fe-55, Co-60, Ni-59, Ni-63, Se-79, Kr-81, Kr-85, Rb-87, Sr-90, Zr-93, Nb-93m, Nb-94, Mo-93, Tc-99, Ru-106, Ag-108m, Cd-109, Cd-113m, Sn-121m, Sn-126, Sb-125, Te-125m, I-129, Cs-134, Cs-135, Cs-137, Ba-133, La-137, Pm-145, Pm-147, Sm-151, Eu-152, Eu-154, Eu-155, Ho-163, Ho-166m, Hf-178n, Pt-193, Tl-204, Pb-210, Po-210, Ra-226, Ra-228, Ac-227, Th-228, Th-229, Th-230, Th-232, Pa-231, U-232, U-233, U-234, U-235, U-236, U-238, Np-237, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244*, Am-241, Am-242m, Am-243, Cm-242, Cm-243, Cm-244, Cm-245, Cm-246, Cm-247*, Cm-248, Cf-250, Cf-251.

(* Pu-244 is produced from Cm-248, Cm-247 is produced from Cf-251.)

3 Radionuclide Data

3.1 Decay Chains

Following the decay chain simplification process outlined above, three types of decay chain are required to specify decays of the radionuclides of interest:

- Direct/simple decay, where the first descendent is a stable nuclide.
- Short chain decay, where only two or three radioactive members are present.
- Long chain decay.

Direct/Simple Decay

The following radionuclides are considered to undergo direct decay to a stable nuclide:

H-3, Be-10, C-14, Na-22, Al-26, Cl-36, Ar-39, K-40, Ca-41, Fe-55, Co-60, Ni-59, Ni-63, Se-79, Kr-81, Kr-85, Rb-87, Sr-90, Zr-93, Nb-93m, Nb-94, Mo-93, Tc-99, Ru-106, Ag-108m, Cd-109, Cd-113m, Sn-121m, Sn-126, Sb-125, Te-125m, I-129, Cs-134, Cs-135, Cs-137, Ba-133, La-137, Pm-145, Pm-147, Sm-147, Sm-151, Eu-152, Eu-154, Eu-155, Ho-163, Ho-166m, Hf-178n, Pt-193, Tl-204.

Note that this list includes the following radionuclides that do not decay directly to a stable radionuclide, but are considered to do so by applying the decay chain simplification rule described above:

- Ru-106, Ag-108m, Cd-113m, Sn-121m, Sn-126 and Cs-137
- Sr-90 is also assumed to decay directly to a stable nuclide, because of the short half-life of Y-90.

For radionuclides Pm-147 and Eu-152, it is noted that the radioactive progeny radionuclides (Sm-147 or Gd-152) are so long-lived that they are also considered to decay to stable products.

Short Decay Chains

Noting the above simplifications, radionuclides chains involving only two or three members comprise the following.

- Mo-93 → Nb-93m
- Zr-93 → Nb-93m
- Zr-95 → Nb-95[4]
- Sb-125 → Te-125m

Long Decay Chains

Radionuclides of interest that are part of long chain decay series are illustrated in Figure 1 to Figure 4. These show, respectively, the:

- 4n decay chain, also known as the Th-232 decay chain, which is headed by Cm-244 and Cf-252[5];
- 4n+1 decay chain, which does not occur naturally, and is headed by Cf-249[6];
- 4n+2 decay chain, also known as the U-238 decay chain, which is headed by Am-242m and Cf-250;
- 4n+3 decay chain, also known as the U-235 decay chain, which is headed by Cm-243 and Cf-251.

Consideration of the aforementioned chain simplification selection criteria was applied to long chain decay radionuclides in order to identify those radionuclides that do not need to be modelled explicitly. Note that for completeness, radionuclides assumed to be in secular equilibrium with a parent are shown in the Figures, along with their half-lives (in years), which are shown in red for radionuclides that do not need to be treated explicitly.

It should also be noted that although Po-210 has a relatively short half life (0.379 y), it has been explicitly *included* in the reduced chains in Figure 5. This is because although for some assessment calculations, e.g. vault release and geosphere migration calculations, it can be neglected or treated as present in secular equilibrium, with its parent Pb-210 (half-life of 22.3 y), in other cases, e.g. in some biosphere calculations, it is necessary to represent Po-210 explicitly because its bio-physiological characteristics are very different to that Pb-210. Whether to treat Po-210 as in secular equilibrium with Pb-210, or explicitly, is an assessment modelling decision.

[4] NB 99% decays directly to Nb-95, and 1% first to Nb-95m (which is not in the radionuclides of interest as a result of the considerations outlined above) and thence to Nb-95,

[5] Cf-252 is not in the list of radionuclides of interest, but is included in the decay chain figure for illustrative purposes.

[6] Cf-249 is also not in the list of radionuclides of interest, but is included in the decay chain figure for illustrative purposes.

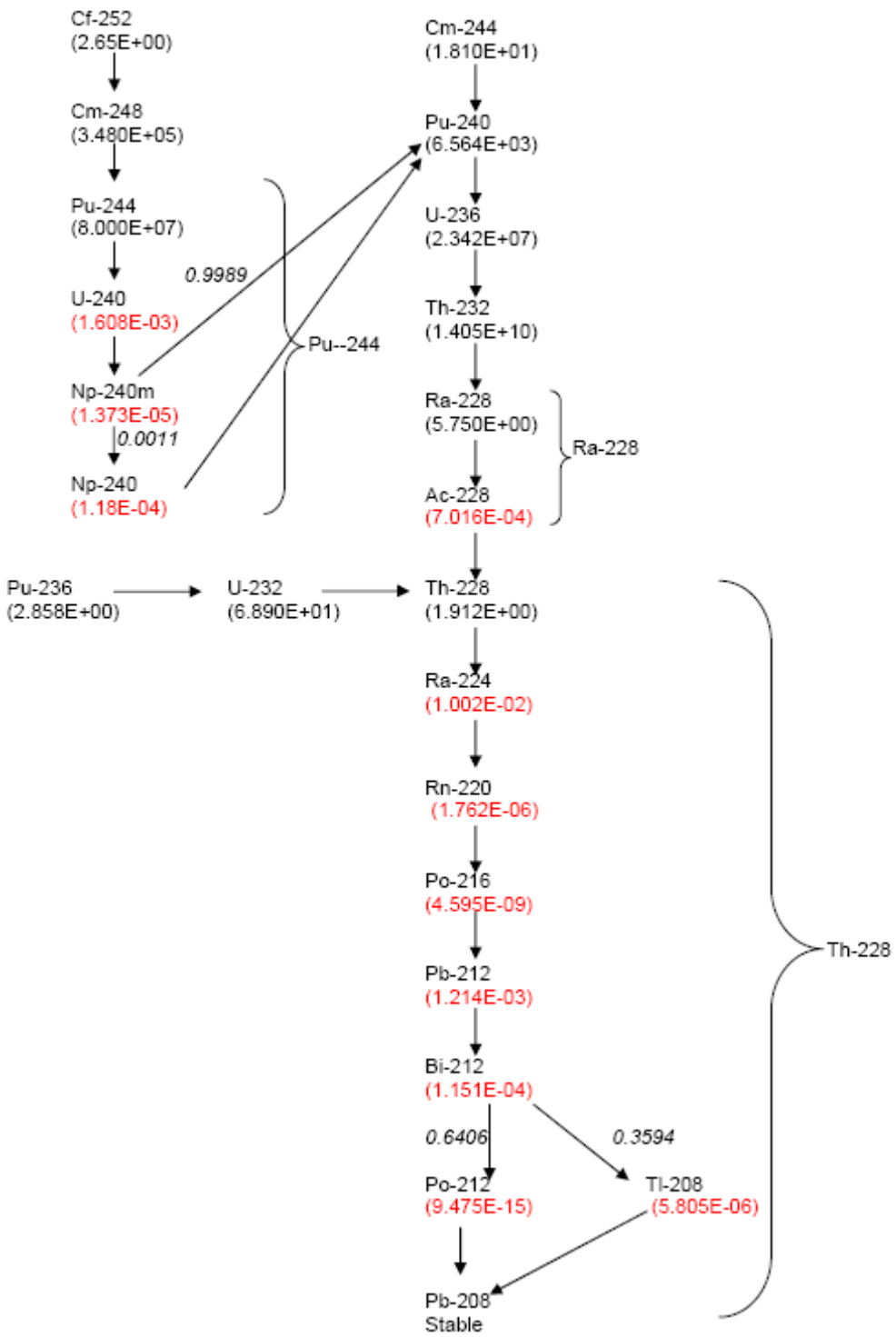

Figure 1: 4n (Th-232) decay chain (half lives in brackets, in years).

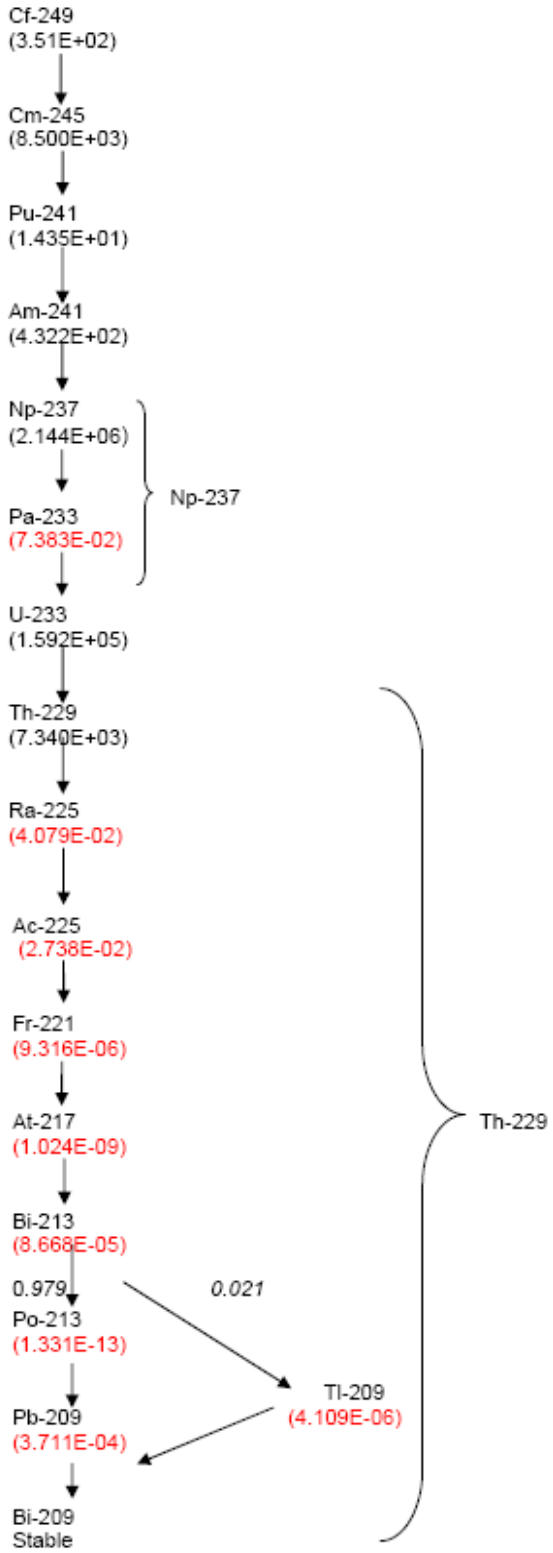

Figure 2: 4n+1 decay chain (headed by Cf-249/Cm-245; half lives in brackets, in years).[7]

[7] U-237 omitted due to very small decay fraction and short half life.

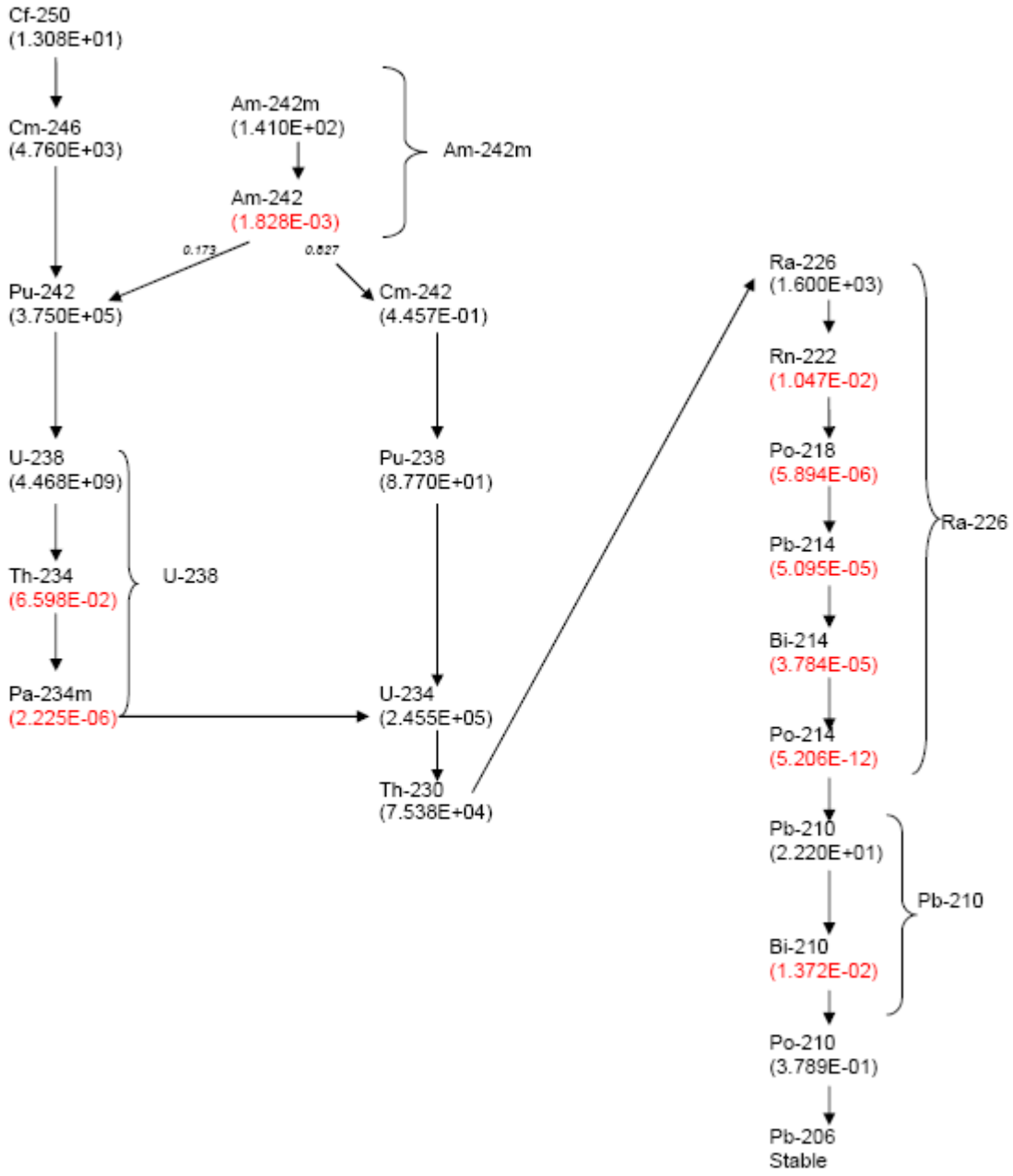

Figure 3: 4n+2 (U-238) decay chain (half lives in brackets, in years).[8]

[8] Np-238, Pa-234, Rn-218, Tl-210, Hg-206 and Tl-206 are excluded due to small decay fractions and very short half lives. Note also that Rn-222 is shown to be in secular equilibrium with Ra-226, but for certain calculations (e.g. the gas phase) it may be considered in its own right.

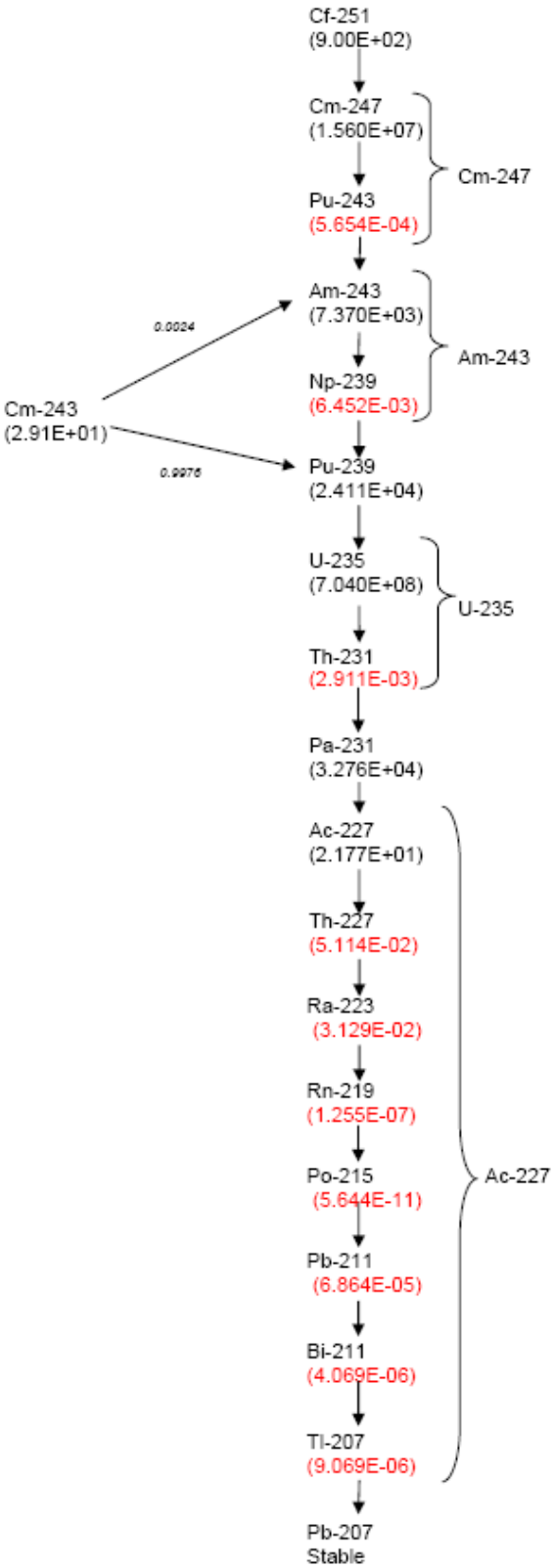

Figure 4: 4n+3 (U-235) decay chain (half lives in brackets, in years).[9]

[9] Note that Fr-223, At-219 and Po-211 are omitted due to their small branching ratios and short half lives.

Radioelements such as Cf are included in the above chains, but are typically screened out from detailed performance assessment calculations. Such screening is not in the remit of the present report, but nonetheless, it is useful to present simplified decay chains that show the main radionuclides typically of interest. The main features are illustrated in Figure 5.

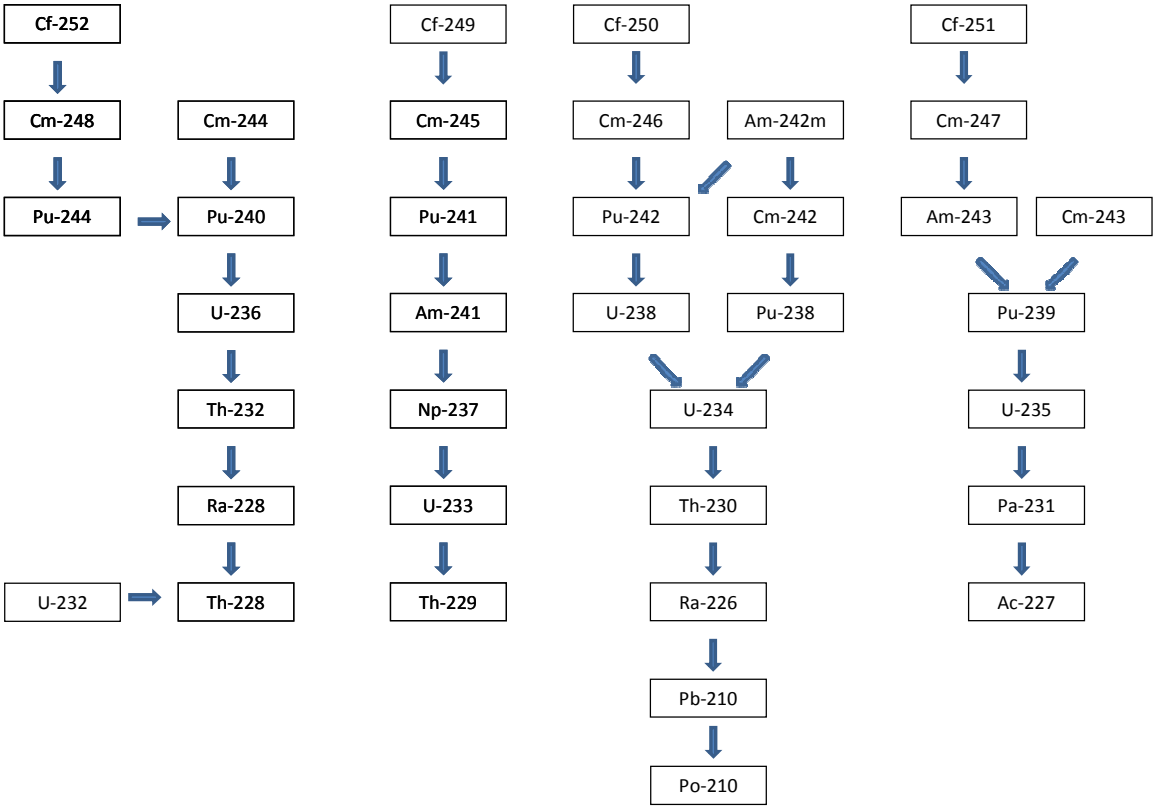

Figure 5: Schematic of simplified long chain decay radionuclides.

3.2 Decay Data

Table 1 below provides important decay data taken from ICRP 107 (ICRP, 2008). This lists both the radionuclides of interest and those assumed to be in secular equilibrium with them. This is of use when considering dose factors that need to take into account contributions to dose from such radionuclides. This table is ordered by radionuclide according to atomic number and provides:

- Half-lives.
- Progeny assumed to be in secular equilibrium and relevant data, including branching ratios. Very minor modes of decay (<1E-05) are neglected.
- Decay modes (A = alpha, B-/+ = beta minus/plus, EC = electron capture, IT = isomeric transition, SF = spontaneous fission).
- Transition energies including total transition energies incorporating contributions from radionuclides in secular equilibrium.

Table 1: Radionuclide Decay Data Including Radionuclides in Secular Equilibrium

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
H-3	-	1.232E+01	B-	0	0.006	0	0.006	1	0	0.006	0	0.006
Be-10	-	1.510E+06	B-	0	0.253	0	0.253	1	0	0.253	0	0.253
C-14	-	5.700E+03	B-	0	0.050	0	0.050	1	0	0.050	0	0.050
Na-22	-	2.602E+00	ECB+	0	0.194	2.193	2.387	1	0	0.194	2.193	2.387
Al-26	-	7.170E+05	ECB+	0	0.444	2.675	3.120	1	0	0.444	2.675	3.120
Cl-36	-	3.010E+05	B-ECB+	0	0.273	0.000	0.273	1	0	0.273	0.000	0.273
Ar-39	-	2.690E+02	B-	0	0.219	0	0.219	1	0	0.219	0	0.219
K-40	-	1.251E+09	B-ECB+	0	0.522	0.157	0.679	1	0	0.522	0.157	0.679
Ca-41	-	1.020E+05	EC	0	0.003	0.001	0.003	1	0	0.003	0.001	0.003
Fe-55	-	2.737E+00	EC	0	0.004	0.002	0.006	1	0	0.004	0.002	0.006
Co-60	-	5.271E+00	B-	0	0.097	2.504	2.601	1	0	0.097	2.504	2.601
Ni-59	-	1.010E+05	ECB+	0	0.005	0.002	0.007	1	0	0.005	0.002	0.007

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
Ni-63	-	1.001E+02	B-	0	0.017	0	0.017	1	0	0.017	0	0.017
Se-79	-	2.950E+05	B-	0	0.053	0	0.053	1	0	0.053	0	0.053
Kr-81	-	2.290E+05	EC	0	0.005	0.007	0.012	1	0	0.005	0.007	0.012
Kr-85	-	1.076E+01	B-	0	0.251	0.002	0.253	1	0	0.251	0.002	0.253
Rb-87	-	4.923E+10	B-	0	0.115	0	0.115	1	0	0.115	0	0.115
Sr-90	Sr-90	2.879E+01	B-	0	0.196	0	0.196	1	0	1.129	0	1.129
	Y-90	7.312E-03	B-	0	0.933	0	0.933	1				
Zr-93	-	1.530E+06	B-	0	0.019	0	0.019	1	0	0.019	0	0.019
Nb-93m	-	1.613E+01	IT	0	0.029	0.002	0.031	1	0	0.029	0.002	0.031
Nb-94	-	2.030E+04	B-	0	0.168	1.558	1.727	1	0	0.168	1.558	1.727
Mo-93	-	4.000E+03	EC	0	0.006	0.011	0.016	1	0	0.006	0.011	0.016
Tc-99	-	2.111E+05	B-	0	0.101	0	0.101	1	0	0.101	0	0.101
Ru-106	Ru-106	1.023E+00	B-	0	0.010	0	0.010	1	0	1.421	0.206	1.627

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
	Rh-106	9.443E-07	B-	0	1.411	0.206	1.617	1				
Ag-108m	-	4.180E+02	ECIT	0	0.016	1.621	1.637	1	0	0.016	1.621	1.637
Cd-109	-	1.263E+00	EC	0	0.083	0.027	0.109	1	0	0.083	0.027	0.109
Cd-113m	-	1.410E+01	B-IT	0	0.185	0	0.185	1	0	0.185	0	0.185
Sn-121m	Sn-121m	4.390E+01	ITB-	0	0.035	0.005	0.041	1	0	0.125	0.005	0.130
	Sn-121	3.084E-03	B-	0	0.116	0	0.116	0.776				
Sn-126	Sn-126	2.300E+05	B-	0	0.138	0.057	0.195	1	0	0.820	1.991	2.811
	Sb-126m	3.641E-05	B-IT	0	0.632	1.548	2.180	1				
	Sb-126	3.381E-02	B-	0	0.355	2.755	3.120	0.14				
Sb-125	-	2.759E+00	B-	0	0.101	0.437	0.538	1	0	0.101	0.437	0.538
Te-125m	-	1.572E-01	IT	0	0.109	0.036	0.145	1	0	0.109	0.036	0.145

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
I-129	-	1.570E+07	B-	0	0.065	0.025	0.090	1	0	0.065	0.025	0.090
Cs-134	-	2.065E+00	B-EC	0	0.164	1.555	1.719	1	0	0.164	1.555	1.719
Cs-135	-	2.300E+06	B-	0	0.089	0	0.089	1	0	0.089	0	0.089
Cs-137	Cs-137	3.017E+01	B-	0	0.188	0	0.188	1	0	0.250	0.563	0.813
	Ba-137m	4.852E-06	IT	0	0.065	0.596	0.662	0.944				
Ba-133	-	1.052E+01	EC	0	0.055	0.403	0.459	1	0	0.055	0.403	0.458
La-137	-	6.000E+04	EC	0	0.007	0.025	0.032	1	0	0.007	0.025	0.032
Pm-145	-	1.770E+01	ECA	0	0.013	0.032	0.044	1	0	0.013	0.032	0.044
Pm-147	-	2.623E+00	B-	0	0.062	0	0.062	1	0	0.062	0	0.062
Sm-147	-	1.060E+11	A	2.311	0	0	2.311	1	2.3105	0	0	2.311
Sm-151	-	9.000E+01	B-	0	0.020	0	0.020	1	0	0.020	0	0.020
Eu-152	-	1.354E+01	ECB+B-	0	0.129	1.176	1.305	1	0	0.129	1.176	1.305
Eu-154	-	8.593E+00	B-EC	0	0.273	1.249	1.522	1	0	0.273	1.249	1.522

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
Eu-155	-	4.761E+00	B-	0	0.065	0.061	0.126	1	0	0.065	0.061	0.126
Ho-163	-	4.570E+03	EC	0	0.001	0	0.001	1	0	0.001	0	0.001
Ho-166m	-	1.200E+03	B-	0	0.150	1.625	1.775	1	0	0.150	1.625	1.775
Hf-178n	-	3.100E+01	IT	0	0.211	2.238	2.450	1	0	0.211	2.238	2.450
Pt-193	-	5.000E+01	EC	0	0.007	0.003	0.010	1	0	0.007	0.003	0.010
Tl-204	-	3.780E+00	B-EC	0	0.237	0.001	0.239	1	0	0.237	0.001	0.239
Pb-210	Pb-210	2.220E+01	B-A	0	0.040	0.005	0.046	1	0	0.429	0.005	0.435
	Bi-210	1.372E-02	B-A	0	0.389	0	0.389	1				
Po-210	-	3.789E-01	A	5.407	0	0	5.407	1	5.407	0	0	5.407
Ra-226	Ra-226	1.600E+03	A	4.860	0.004	0.007	4.872	1	24.40	0.962	1.740	27.10
	Rn-222	1.047E-02	A	5.590	0	0.000	5.590	1				
	Po-218	5.894E-06	A B-	6.113	0	0	6.113	1				

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
	Pb-214	5.095E-05	B-	0	0.295	0.253	0.548	0.9998				
	Bi-214	3.784E-05	B-A	0.001	0.663	1.479	2.144	1				
	Po-214	5.206E-12	A	7.8333	0	0	7.833	0.9998				
Ra-228	Ra-228	5.750E+00	B-	0	0.013	0.003	0.016	1	0	0.463	0.870	1.333
	Ac-228	7.016E-04	B-	0	0.449	0.867	1.317	1				
Ac-227	Ac-227	2.177E+01	B-A	0.069	0.015	0.001	0.085	1	32.83	1.132	0.445	34.40
	Th-227	5.114E-02	A	5.988	0.076	0.132	6.195	0.9862				
	Ra-223	3.129E-02	A	5.770	0.078	0.141	5.989	1				
	Rn-219	1.255E-07	A	6.880	0.007	0.059	6.946	1				
	Po-215	5.644E-11	A	7.526	0	0.000	7.526	1				
	Pb-211	6.864E-05	B-	0	0.454	0.064	0.519	1				
	Bi-211	4.069E-06	A B-	6.676	0.010	0.047	6.733	1				
	Tl-207	9.069E-06	B-	0	0.495	0.002	0.498	0.9972				

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
Th-228	Th-228	1.912E+00	A	5.496	0.021	0.004	5.520	1	32.53	0.924	1.471	34.93
	Ra-224	1.002E-02	A	5.777	0.002	0.010	5.789	1				
	Rn-220	1.762E-06	A	6.404	0	0.0006	6.4046	1				
	Po-216	4.595E-09	A	6.906	0	0	6.906	1				
	Pb-212	1.214E-03	B-	0	0.177	0.145	0.322	1				
	Bi-212	1.151E-04	B-A	2.216	0.505	0.104	2.825	1				
	Po-212	9.475E-15	A	8.954	0	0	8.954	0.641				
	Tl-208	5.805E-06	B-	0	0.611	3.360	3.972	0.359				
Th-229	Th-229	7.340E+03	A	4.958	0.122	0.097	5.176	1	32.95	0.916	0.331	34.20
	Ra-225	4.079E-02	B-	0	0.105	0.015	0.119	1				
	Ac-225	2.738E-02	A	5.892	0.025	0.017	5.934	1				
	Fr-221	9.316E-06	A	6.420	0.009	0.029	6.458	1				
	At-217	1.024E-09	A	7.201	0	0.000	7.201	1				

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
	Bi-213	8.668E-05	B-A	0.125	0.444	0.128	0.696	0.9999				
	Po-213	1.331E-13	A	8.537	0	0	8.537	0.979				
	Tl-209	4.109E-06	B-	0	0.6875	2.1426	2.8302	0.0209				
	Pb-209	3.711E-04	B-	0	0.197	0	0.197	0.9999				
Th-230	-	7.538E+04	A	4.754	0.015	0.002	4.770	1	4.754	0.015	0.002	4.770
Th-232	-	1.405E+10	A	4.069	0.013	0.002	4.083	1	4.069	0.013	0.002	4.083
Pa-231	-	3.276E+04	A	5.059	0.054	0.045	5.157	1	5.059	0.054	0.045	5.157
U-232	-	6.890E+01	A	5.395	0.016	0.002	5.414	1	5.395	0.016	0.002	5.414
U-233	-	1.592E+05	A	4.901	0.006	0.001	4.908	1	4.901	0.006	0.001	4.908
U-234	-	2.455E+05	A	4.843	0.014	0.002	4.859	1	4.843	0.014	0.002	4.859
U-235	U-235	7.040E+08	A	4.469	0.053	0.167	4.689	1	4.469	0.215	0.194	4.878
	Th-231	2.911E-03	B-	0	0.162	0.027	0.189	1				
U-236	-	2.342E+07	A	4.559	0.011	0.002	4.572	1	4.559	0.011	0.002	4.572

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
U-238	U-238	4.468E+09	A SF	4.258	0.009	0.001	4.269	1	4.258	0.889	0.028	5.175
	Th-234	6.598E-02	B-	0	0.062	0.011	0.073	1				
	Pa-234m	2.225E-06	B-IT	0	0.817	0.016	0.833	1				
Np-237	Np-237	2.144E+06	A	4.849	0.068	0.035	4.952	1	4.849	0.283	0.258	5.390
	Pa-233	7.383E-02	B-	0	0.215	0.223	0.438	1				
Pu-238	-	8.770E+01	A SF	5.580	0.011	0.002	5.593	1	5.580	0.011	0.002	5.593
Pu-239	-	2.411E+04	A	5.236	0.007	0.001	5.244	1	5.236	0.007	0.001	5.244
Pu-240	-	6.564E+03	A SF	5.243	0.011	0.002	5.256	1	5.243	0.011	0.002	5.256
Pu-241	-	1.435E+01	B-A	0.000	0.005	0	0.005	1	0.000	0.005	0	0.005
Pu-242	-	3.750E+05	A SF	4.974	0.009	0.002	4.985	1	4.974	0.009	0.002	4.985
Pu-244	Pu-244	8.000E+07	A SF	4.651	0.020	0.021	4.692	1	4.651	0.824	0.353	5.829
	U-240	1.608E-03	B-	0	0.128	0.010	0.137	0.9988				
	Np-240m	1.373E-05	B-IT	0	0.678	0.323	1.000	0.9988				

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
Am-241	-	4.322E+02	A	5.571	0.037	0.029	5.638	1	5.571	0.037	0.029	5.638
Am-242m	Am-242m	1.410E+02	ITA	0.024	0.044	0.006	0.073	1	0.024	0.224	0.024	0.272
	Am-242	1.828E-03	B-EC	0	0.181	0.019	0.199	0.996				
Am-243	Am-243	7.370E+03	A	5.358	0.023	0.059	5.440	1	5.358	0.286	0.243	5.887
	Np-239	6.452E-03	B-	0	0.262	0.185	0.447	1				
Cm-242	-	4.457E-01	A SF	6.204	0.010	0.002	6.216	1	6.204	0.010	0.002	6.216
Cm-243	-	2.910E+01	A EC	5.893	0.134	0.135	6.162	1	5.893	0.134	0.135	6.162
Cm-244	-	1.810E+01	A SF	5.892	0.008	0.002	5.901	1	5.892	0.008	0.002	5.901
Cm-245	-	8.500E+03	A SF	5.447	0.082	0.108	5.638	1	5.447	0.082	0.108	5.638
Cm-246	-	4.760E+03	A SF	5.465	0.009	0.005	5.479	1	5.465	0.009	0.005	5.479
Cm-247	Cm-247	1.560E+07	A	5.029	0.011	0.314	5.354	1	5.029	0.184	0.340	5.552
	Pu-243	5.654E-04	B-	0	0.173	0.026	0.199	1				

Parent	Radionuclides in Secular Equilibrium	Half Life (y)	Decay Modes	Radionuclide Transformation Energies				Branching Ratio	Total Transformation Energies Including Contributions from Radionuclides in Secular Equilibrium			
				Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)		Alpha Energy (MeV)	Beta Energy (MeV)	Photon Energy (MeV)	Total Energy (MeV)
Cm-248	-	3.480E+05	A SF	4.721	0.772	1.313	6.805	1	4.721	0.772	1.313	6.805
Cf-249	-	3.510E+02	A SF	5.926	0.040	0.328	6.294	1	5.926	0.040	0.328	6.294
Cf-250	-	1.308E+01	A SF	6.117	0.010	0.011	6.138	1	6.117	0.010	0.011	6.138
Cf-251	-	9.000E+02	A	5.879	0.171	0.125	6.174	1	5.879	0.171	0.125	6.174

3.3 Committed Effective Dose per Unit Intake

Appropriate values of committed effective dose per unit intake for adults are given below.

Table 2 shows committed effective dose per unit ingestion for an adult. Table 3 gives committed effective doses per unit inhalation of a vapour, and Table 4 gives committed effective doses per unit inhalation of an aerosol for an adult. For all three tables dose values are taken from Federal Guidance Report No.13 except those marked * which have been added from ICRP Publication 72. The summation of daughters assumed to be in secular equilibrium is shown. Note that such dose factors are effectively zero for noble gases as they are not readily metabolised.

Where progeny are considered to be present in secular equilibrium they take the same inhalation class as their parent.

Table 2: Committed effective dose per unit ingestion for an adult

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
H-3	H-3	1.232E+01	4.19E-11	1	4.19E-11
Be-10	Be-10	1.510E+06	1.14E-09	1	1.14E-09
C-14	C-14	5.700E+03	5.81E-10	1	5.81E-10
Na-22	Na-22	2.602E+00	3.18E-09	1	3.18E-09
Al-26	Al-26	7.170E+05	3.50E-09	1	3.50E-09
Cl-36	Cl-36	3.010E+05	9.29E-10	1	9.29E-10
Ar-39	Ar-39	2.690E+02		1	0.00E+00
K-40	K-40	1.251E+09	6.16E-09	1	6.16E-09
Ca-41	Ca-41	1.020E+05	1.93E-10	1	1.93E-10
Fe-55	Fe-55	2.737E+00	3.31E-10	1	3.31E-10
Co-60	Co-60	5.271E+00	3.42E-09	1	3.42E-09
Ni-59	Ni-59	1.010E+05	6.30E-11	1	6.30E-11
Ni-63	Ni-63	1.001E+02	1.52E-10	1	1.52E-10
Se-79	Se-79	2.950E+05	2.89E-09	1	2.89E-09
Kr-81	Kr-81	2.290E+05		1	0.00E+00
Kr-85	Kr-85	1.076E+01		1	0.00E+00

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
Rb-87	Rb-87	4.923E+10	1.47E-09	1	1.47E-09
Sr-90	Sr-90	2.879E+01	2.77E-08	1	3.04E-08
	Y-90	7.312E-03	2.69E-09	1	
Zr-93	Zr-93	1.530E+06	1.11E-09	1	1.11E-09
Nb-93m	Nb-93m	1.613E+01	1.24E-10	1	1.24E-10
Nb-94	Nb-94	2.030E+04	1.74E-09	1	1.74E-09
Mo-93	Mo-93	4.000E+03	3.16E-09	1	3.16E-09
Tc-99	Tc-99	2.111E+05	6.42E-10	1	6.42E-10
Ru-106	Ru-106	1.023E+00	7.01E-09	1	7.01E-09
	Rh-106	9.443E-07		1	
Ag-108m	Ag-108m	4.180E+02	2.36E-09	1	2.36E-09
Cd-109	Cd-109	1.263E+00	2.00E-09	1	2.00E-09
Cd-113m	Cd-113m	1.410E+01	2.30E-08	1	2.30E-08
Sn-121m	Sn-121m	4.390E+01	3.82E-10	1	5.59E-10
	Sn-121	3.084E-03	2.28E-10	0.776	
Sn-126	Sn-126	2.300E+05	4.77E-09	1	5.15E-09
	Sb-126m	3.641E-05	3.60E-11	1	
	Sb-126	3.381E-02	2.46E-09	0.14	
Sb-125	Sb-125	2.759E+00	1.13E-09	1	1.13E-09
Te-125m	Te-125m	1.572E-01	8.72E-10	1	8.72E-10
I-129	I-129	1.570E+07	1.06E-07	1	1.06E-07
Cs-134	Cs-134	2.065E+00	1.92E-08	1	1.92E-08
Cs-135	Cs-135	2.300E+06	2.00E-09	1	2.00E-09
Cs-137	Cs-137	3.017E+01	1.36E-08	1	1.36E-08
	Ba-137m	4.852E-06		0.944	
Ba-133	Ba-133	1.052E+01	1.53E-09	1	1.53E-09

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
La-137	La-137	6.000E+04	8.27E-11	1	8.27E-11
Pm-145	Pm-145	1.770E+01	1.16E-10	1	1.16E-10
Pm-147	Pm-147	2.623E+00	2.61E-10	1	2.61E-10
Sm-147	Sm-147	1.060E+11	4.95E-08	1	4.95E-08
Sm-151	Sm-151	9.000E+01	9.80E-11	1	9.80E-11
Eu-152	Eu-152	1.354E+01	1.37E-09	1	1.37E-09
Eu-154	Eu-154	8.593E+00	2.04E-09	1	2.04E-09
Eu-155	Eu-155	4.761E+00	3.26E-10	1	3.26E-10
Ho-163	Ho-163	4.570E+03		1	
Ho-166m	Ho-166m	1.200E+03	1.98E-09	1	1.98E-09
Hf-178n	Hf-178n	3.100E+01	4.74E-09	1	4.74E-09
Pt-193	Pt-193	5.000E+01	3.10E-11	1	3.10E-11
Tl-204	Tl-204	3.780E+00	1.19E-09	1	1.19E-09
Pb-210	Pb-210	2.220E+01	6.96E-07	1	6.97E-07
	Bi-210	1.372E-02	1.31E-09	1	
Po-210	Po-210	3.789E-01	1.21E-06	1	1.21E-06
Ra-226	Ra-226	1.600E+03	2.80E-07	1	2.80E-07
	Rn-222	1.047E-02		1	
	Po-218	5.894E-06		1	
	Pb-214	5.095E-05	1.39E-10	0.9998	
	Bi-214	3.784E-05	1.12E-10	1	
	Po-214	5.206E-12		0.9998	
Ra-228	Ra-228	5.750E+00	6.97E-07	1	6.97E-07
	Ac-228	7.016E-04	4.01E-10	1	
Ac-227	Ac-227	2.177E+01	3.23E-07	1	4.36E-07
	Th-227	5.114E-02	9.02E-09	0.9862	

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
	Ra-223	3.129E-02	1.04E-07	1	
	Rn-219	1.255E-07		1	
	Po-215	5.644E-11		1	
	Pb-211	6.864E-05	1.78E-10	1	
	Bi-211	4.069E-06		1	
	Tl-207	9.069E-06		0.9972	
Th-228	Th-228	1.912E+00	7.20E-08	1	1.43E-07
	Ra-224	1.002E-02	6.45E-08	1	
	Rn-220	1.762E-06		1	
	Po-216	4.595E-09		1	
	Pb-212	1.214E-03	5.98E-09	1	
	Bi-212	1.151E-04	2.59E-10	1	
	Po-212	9.475E-15		0.6406	
	Tl-208	5.805E-06		0.3594	
Th-229	Th-229	7.340E+03	5.00E-07	1	6.38E-07
	Ra-225	4.079E-02	9.95E-08	1	
	Ac-225	2.738E-02	3.85E-08	1	
	Fr-221	9.316E-06		1	
	At-217	1.024E-09		1	
	Bi-213	8.668E-05	1.98E-10	0.9999	
	Po-213	1.331E-13		0.979	
	Tl-209	4.109E-06		0.0209	
	Pb-209	3.711E-04	5.67E-11	0.9999	
Th-230	Th-230	7.538E+04	2.14E-07	1	2.14E-07
Th-232	Th-232	1.405E+10	2.31E-07	1	2.31E-07
Pa-231	Pa-231	3.276E+04	4.79E-07	1	4.79E-07

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
U-232	U-232	6.890E+01	3.36E-07	1	3.36E-07
U-233	U-233	1.592E+05	5.13E-08	1	5.13E-08
U-234	U-234	2.455E+05	4.95E-08	1	4.95E-08
U-235	U-235	7.040E+08	4.67E-08	1	4.70E-08
	Th-231	2.911E-03	3.36E-10	1	
U-236	U-236	2.342E+07	4.69E-08	1	4.69E-08
U-238	U-238	4.468E+09	4.45E-08	1	4.79E-08
	Th-234	6.598E-02	3.40E-09	1	
	Pa-234m	2.225E-06		1	
Np-237	Np-237	2.144E+06	1.07E-07	1	1.08E-07
	Pa-233	7.383E-02	8.78E-10	1	
Pu-238	Pu-238	8.770E+01	2.28E-07	1	2.28E-07
Pu-239	Pu-239	2.411E+04	2.51E-07	1	2.51E-07
Pu-240	Pu-240	6.564E+03	2.51E-07	1	2.51E-07
Pu-241	Pu-241	1.435E+01	4.75E-09	1	4.75E-09
Pu-242	Pu-242	3.750E+05	2.38E-07	1	2.38E-07
Pu-244	Pu-244	8.000E+07	2.40E-07*	1	2.41E-07
	U-240	1.608E-03	1.11E-09	0.9988	
	Np-240m	1.373E-05		0.9988	
Am-241	Am-241	4.322E+02	2.04E-07	1	2.04E-07
Am-242m	Am-242m	1.410E+02	1.91E-07	1	1.91E-07
	Am-242	1.828E-03	2.96E-10	0.9955	
Am-243	Am-243	7.370E+03	2.03E-07	1	2.04E-07
	Np-239	6.452E-03	7.99E-10	1	
Cm-242	Cm-242	4.457E-01	1.17E-08	1	1.17E-08
Cm-243	Cm-243	2.910E+01	1.49E-07	1	1.49E-07

Parent	Decay Chain	Half Life (y)	Dose per unit ingestion (Sv/Bq)	Branching Ratio	Dose per unit ingestion (Sv/Bq)
Cm-244	Cm-244	1.810E+01	1.23E-07	1	1.23E-07
Cm-245	Cm-245	8.500E+03	2.08E-07	1	2.08E-07
Cm-246	Cm-246	4.760E+03	2.05E-07	1	2.05E-07
Cm-247	Cm-247	1.560E+07	1.91E-07	1	1.91E-07
	Pu-243	5.654E-04	8.52E-11	1	
Cm-248	Cm-248	3.480E+05	7.70E-07*	1	7.70E-07
Cf-249	Cf-249	3.510E+02	3.52E-07	1	3.52E-07
Cf-250	Cf-250	1.308E+01	1.57E-07	1	1.57E-07
Cf-251	Cf-251	9.000E+02	3.59E-07	1	3.59E-07

Table 3: Committed effective doses per unit inhalation of a vapour[10]

Radionuclide	Chemical Form	Dose per unit inhalation (Sv/Bq)
H-3	Tritiated Water	1.83E-11
H-3	Elemental	1.83E-15
H-3	Organic	4.13E-11
C-14	Monoxide	8.01E-13
C-14	Dioxide	6.24E-12
Ni-59	Vapour	8.27E-10
Ni-63	Vapour	1.96E-09
Ru-106	Vapour	1.86E-08
Te-125m	Vapour	1.51E-09
I-129	Vapour	9.59E-08
I-129	Methyl Iodide	7.48E-08

[10] Note that special considerations apply to C-14 labelled methane; such issues will require specific attention in relevant assessment reports.

Table 4: Committed effective doses per unit inhalation of an aerosol for an adult[11]

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
H-3	H-3	M	4.51E-11	1	M	4.51E-11	
Be-10	Be-10	S	3.46E-08	1	S	3.46E-08	Most common compounds are M or S, but S has the larger dose factors.
C-14	C-14	M	2.03E-09	1	M	2.03E-09	
Na-22	Na-22	F	1.28E-09	1	F	1.28E-09	Applies to all common compounds.
Al-26	Al-26	M	1.95E-08	1	M	1.95E-08	Most common compounds are F or M, but M has the larger dose factors.
Cl-36	Cl-36	M	7.32E-09	1	M	7.32E-09	Most common compounds are F or M, but M has the larger dose factors.
Ar-39	Ar-39			1			Noble gas
K-40	K-40	F	2.07E-09	1	F	2.07E-09	Applies to all common compounds.
Ca-41	Ca-41	M	9.48E-11	1	M	9.48E-11	
Fe-55	Fe-55	M	3.88E-10	1	M	3.88E-10	

[11] The assigned inhalation class relate to whether absorption is considered to be fast, medium or slow (F, M or S) from tissue into bodily fluids. The 'default' class indicates the relevant absorption rate for dose calculations; additional explanatory notes are provided where required.

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
Co-60	Co-60	M	1.02E-08	1	M	1.02E-08	
Ni-59	Ni-59	M	1.32E-10	1	M	1.32E-10	
Ni-63	Ni-63	M	4.73E-10	1	M	4.73E-10	
Se-79	Se-79	F	1.14E-09	1	F	1.14E-09	
Kr-81	Kr-81			1			Noble gas
Kr-85	Kr-85			1			Noble gas
Rb-87	Rb-87	F	4.97E-10	1	F	4.97E-10	Applies to all common compounds.
Sr-90	Sr-90	M	3.56E-08	1	M	3.70E-08	
	Y-90	Not defined	5.36E-10 (F), 1.39E-09 (M), 1.50E-09 (S)	1	M		Not needed as treated in chain.
Zr-93	Zr-93	M	1.02E-08	1	M	1.02E-08	
Nb-93m	Nb-93m	M	5.06E-10	1	M	5.06E-10	
Nb-94	Nb-94	M	1.07E-08	1	M	1.07E-08	
Mo-93	Mo-93	M	5.92E-10	1	M	5.92E-10	

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
Tc-99	Tc-99	M	4.03E-09	1	M	4.03E-09	
Ru-106	Ru-106	M	2.79E-08	1	M	2.79E-08	
	Rh-106	Not defined		1	M		Not needed as treated in chain.
Ag-108m	Ag-108m	M	7.53E-09	1	M	7.53E-09	
Cd-109	Cd-109	F	8.16E-09	1	F	8.16E-09	Largest dose factors.
Cd-113m	Cd-113m	F	1.10E-07	1	F	1.10E-07	Largest dose factors.
Sn-121m	Sn-121m	M	4.45E-09	1	M	4.63E-09	Most common compounds are F or M, but M has the larger dose factors.
	Sn-121	Not defined	6.03E-11 (F), 2.28-10 (M), 2.49E-10 (S)	0.776	M		Not needed as treated in chain.
Sn-126	Sn-126	M	2.84E-08	1	M	2.88E-08	Most common compounds are F or M, but M has the larger dose factors.
	Sb-126m	M	1.88E-11	1	M		
	Sb-126	M	2.86E-09	0.14	M		
Sb-125	Sb-125	M	4.79E-09	1	M	4.79E-09	

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
Te-125m	Te-125m	M	3.37E-09	1	M	3.37E-09	
I-129	I-129	F	3.59E-08	1	F	3.59E-08	
Cs-134	Cs-134	F	6.69E-09	1	F	6.69E-09	
Cs-135	Cs-135	F	6.89E-10	1	F	6.89E-10	
Cs-137	Cs-137	F	4.67E-09	1	F	4.67E-09	
	Ba-137m	M		0.944	F		Default, but modified to conform to parent.
Ba-133	Ba-133	M	3.15E-09	1	M	3.15E-09	
La-137	La-137	M	3.66E-09	1	M	3.66E-09	Treated consistently with other lanthanides.
Pm-145	Pm-145	M	3.69E-09	1	M	3.69E-09	Treated consistently with other lanthanides.
Pm-147	Pm-147	M	4.94E-09	1	M	4.94E-09	Treated consistently with other lanthanides.
Sm-147	Sm-147	M	9.62E-06	1	M	9.62E-06	Applies to all common compounds.
Sm-151	Sm-151	M	3.98E-09	1	M	3.98E-09	Applies to all common compounds.
Eu-152	Eu-152	M	4.20E-08	1	M	4.20E-08	Applies to all common compounds.
Eu-154	Eu-154	M	5.32E-08	1	M	5.32E-08	Applies to all common compounds.

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
Eu-155	Eu-155	M	6.96E-09	1	M	6.96E-09	Applies to all common compounds.
Ho-163	Ho-163	M		1	M		Applies to all common compounds.
Ho-166m	Ho-166m	M	1.20E-07	1	M	1.20E-07	Applies to all common compounds.
Hf-178n	Hf-178n	F	2.66E-07	1	F	2.66E-07	Most common compounds are F or M, but F has the larger dose factors.
Pt-193	Pt-193	F	2.11E-11	1	F	2.11E-11	Applies to all common compounds.
Tl-204	Tl-204	F	3.96E-10	1	F	3.96E-10	Applies to all common compounds.
Pb-210	Pb-210	M	1.10E-06	1	M	1.19E-06	
	Bi-210	Not defined	1.07E-09 (F), 9.3E-08 (M), 1.33E-07 (S)	1	M		Not needed as treated in chain.
Po-210	Po-210	M	3.27E-06	1	M	3.27E-06	
Ra-226	Ra-226	M	3.46E-06	1	M	3.49E-06	
	Rn-222	Not defined		1	M		Not needed as treated in chain.
	Po-218	M		1	M		

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
	Pb-214	M	1.36E-08	0.9998	M		
	Bi-214	Not defined	7.23E-09 (F), 1.46E-08 (M), 1.54E-08 (S)	1	M		Not needed as treated in chain.
	Po-214	M		0.9998	M		
Ra-228	Ra-228	M	2.64E-06	1	M	2.65E-06	
	Ac-228	Not defined	1.19E-08 (F), 1.19E-08 (M), 1.46E-08 (S)	1	M		Not needed as treated in chain.
Ac-227	Ac-227	M	7.28E-05	1	M	8.86E-05	Assigned to the same type as the higher actinides.
	Th-227	S	6.69E-07	0.9862	M		Default, but modified to conform to parent.
	Ra-223	M	7.44E-06	1	M		
	Rn-219	Not defined		1	M		Not needed as treated in chain.
	Po-215	M		1	M		
	Pb-211	M	1.11E-08	1	M		
	Bi-211	Not		1	M		Not needed as treated in chain.

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
		defined					
	Tl-207	F		0.9972	F		Applies to all common compounds.
Th-228	Th-228	S	3.97E-05	1	S	4.33E-05	
	Ra-224	M	2.97E-06	1	S		Default, but modified to conform to parent.
	Rn-220	Not defined		1	S		Not needed as treated in chain.
	Po-216	M		1	S		Default, but modified to conform to parent.
	Pb-212	M	1.72E-07	1	S		Default, but modified to conform to parent.
	Bi-212	Not defined	9.04E-09 (F), 3.08E-08 (M), 3.32E-08 (S)	1	S		Not needed as treated in chain.
	Po-212	M		0.6406	S		Default, but modified to conform to parent.
	Tl-208	F		0.3594	S		Default, but modified to conform to parent.
Th-229	Th-229	S	7.12E-05	1	S	8.75E-05	
	Ra-225	M	6.26E-06	1	S		Default, but modified to conform to parent.
	Ac-225	Not defined	7.97E-07 (F), 7.39E-06 (M),	1	S		Not needed as treated in chain.

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
			8.49E-06 (S)				
	Fr-221	F		1	S		Applies to all common compounds, but modified to conform to parent.
	At-217	Not defined		1	S		Not needed as treated in chain.
	Bi-213	Not defined	1.05E-08 (F), 2.98E-08 (M), 3.20E-08 (S)	0.9999	S		Not needed as treated in chain.
	Po-213	M		0.979	S		Default, but modified to conform to parent.
	Tl-209	F		0.0209	S		Default, but modified to conform to parent.
	Pb-209	M	5.64E-11	0.9999	S		Default, but modified to conform to parent.
Th-230	Th-230	S	1.40E-05	1	S	1.40E-05	
Th-232	Th-232	S	2.48E-05	1	S	2.48E-05	
Pa-231	Pa-231	M	9.35E-05	1	M	9.35E-05	Similar to lanthanides and higher actinides.
U-232	U-232	M	7.82E-06	1	M	7.82E-06	
U-233	U-233	M	3.55E-06	1	M	3.55E-06	
U-234	U-234	M	3.48E-06	1	M	3.48E-06	

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
U-235	U-235	M	3.09E-06	1	M	3.09E-06	
	Th-231	S	3.34E-10	1	M		Default, but modified to conform to parent.
U-236	U-236	M	3.21E-06	1	M	3.21E-06	
U-238	U-238	M	2.86E-06	1	M	2.87E-06	
	Th-234	S	7.69E-09	1	M		Default, but modified to conform to parent.
	Pa-234m	Not defined		1	S		Not needed as treated in chain.
Np-237	Np-237	M	2.27E-05	1	M	2.27E-05	
	Pa-233	Not defined	1.03E-09, 3.33E-09, 3.86E-09	1	M		Not needed as treated in chain.
Pu-238	Pu-238	M	4.62E-05	1	M	4.62E-05	
Pu-239	Pu-239	M	5.01E-05	1	M	5.01E-05	
Pu-240	Pu-240	M	5.02E-05	1	M	5.02E-05	
Pu-241	Pu-241	M	9.01E-07	1	M	9.01E-07	
Pu-242	Pu-242	M	4.76E-05	1	M	4.76E-05	

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
Pu-244	Pu-244	M	4.70E-05*	1	M	4.70E-05*	
	U-240	M	5.43E-10	0.9988	M		
	Np-240m	M		0.9988	M		
Am-241	Am-241	M	4.17E-05	1	M	4.17E-05	
Am-242m	Am-242m	M	3.70E-05	1	M	3.70E-05	
	Am-242	M	1.73E-08	0.9955	M		
Am-243	Am-243	M	4.12E-05	1	M	4.12E-05	
	Np-239	M	9.33E-10	1	M		
Cm-242	Cm-242	M	5.20E-06	1	M	5.20E-06	
Cm-243	Cm-243	M	3.15E-05	1	M	3.15E-05	
Cm-244	Cm-244	M	2.66E-05	1	M	2.66E-05	
Cm-245	Cm-245	M	4.24E-05	1	M	4.24E-05	
Cm-246	Cm-246	M	4.19E-05	1	M	4.19E-05	
Cm-247	Cm-247	M	3.86E-05	1	M	3.86E-05	

Parent	Decay Chain	Default Inhalation Class	Dose per unit inhalation (Sv/Bq)	Branching Ratio	Chain Inhalation Class	Dose per unit inhalation (Sv/Bq)	Notes on assigned inhalation class
	Pu-243	M	8.29E-11	1	M		
Cm-248	Cm-248	M	1.50E-04*	1	M	1.50E-04*	
Cf-249	Cf-249	M	7.00E-05	1	M	7.00E-05	Applies to all common compounds.
Cf-250	Cf-250	M	3.32E-05	1	M	3.32E-05	Applies to all common compounds.
Cf-251	Cf-251	M	7.11E-05	1	M	7.11E-05	Applies to all common compounds.

3.4 Effective Dose Rates for External Exposure

3.4.1 Effective Dose Rates for Exposure from a Semi-infinite Slab and a Semi-infinite Surface

External dose rates for exposure from a semi-infinite slab including total dose rates taking contributions from short-lived progeny into account are shown in Table 5, along with equivalent dose rates for exposure from a semi-infinite surface. In both cases, values quoted are based upon the US Environmental Protection Agency Federal Guidance Report No. 13 (USEPA, 2002), which is the primary authoritative international source for such data.

Note that the surface and slab dose rates have units of Sv s^{-1} per Bq m^{-2} and Sv s^{-1} per Bq m^{-3} respectively. They have, therefore, to be scaled by appropriate factors if different units are required. Specifically, if dose rates per kilogram are required for slab dose factors, a density of 1600 kg m^{-3} should be used as this is the density underlying the calculations presented in the USEPA report.

In each case, a standard geometrical configuration is adopted (1 m above the slab or plane). It is essential to include contributions from progeny treated in secular equilibrium, as these often dominate the dose.

3.4.2 Irradiation from a Point Source

Effective photon dose rates, or more strictly air kerma values, for exposure from point sources are also presented in Table 5. In calculating these dose rates, the higher kerma values quoted in ICRP 107 (ICRP, 2008) are utilised, as these include the contribution of annihilation photons and photons and neutrons from spontaneous fission. Beta dose rates are not included in this calculation (but can be calculated according to the approach presented in Appendix D).

To a first approximation, the air kerma values can be treated as if they were doses, but strictly they should be multiplied by the ratio of the mass stopping power of tissue to that of air (typically ~ 1.07). Note also that this would give the dose rate to a small element of tissue. Unlike effective dose, no allowance is made for body shielding, so the importance of, e.g., soft x-rays, is over-emphasised.

The effective dose at distances other than 1m can then be estimated using the inverse square law.

Table 5: Effective Dose Rates for Exposure from a Semi-infinite Slab and a Semi-infinite Surface, and Air Kerma Values for Irradiation from a Point Source

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
H-3	H-3	1	0	0	0	0	0	0
Be-10	Be-10	1	3.41E-18	5.38E-21	0	3.41E-18	5.38E-21	0
C-14	C-14	1	1.28E-20	5.90E-23	0	1.28E-20	5.9E-23	0
Na-22	Na-22	1	2.05E-15	6.90E-17	7.80E-17	2.05E-15	6.9E-17	7.8E-17
Al-26	Al-26	1	2.47E-15	8.84E-17	8.87E-17	2.47E-15	8.84E-17	8.87E-17
Cl-36	Cl-36	1	1.12E-17	1.33E-20	5.38E-21	1.12E-17	1.33E-20	5.38E-21
Ar-39	Ar-39	1	2.53E-18	4.30E-21	0	2.53E-18	4.3E-21	0
K-40	K-40	1	2.03E-16	5.33E-18	5.15E-18	2.03E-16	5.33E-18	5.15E-18
Ca-41	Ca-41	1	0	0	0	0	0	0
Fe-55	Fe-55	1	0	0	4.93E-27	0	0	4.93E-27
Co-60	Co-60	1	2.30E-15	8.24E-17	8.53E-17	2.3E-15	8.24E-17	8.53E-17
Ni-59	Ni-59	1	0	0	5.88E-22	0	0	5.88E-22
Ni-63	Ni-63	1	0	0	0	0	0	0

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
Se-79	Se-79	1	1.65E-20	8.21E-23	0	1.65E-20	8.21E-23	0
Kr-81	Kr-81	1	5.99E-18	1.48E-19	2.12E-17	5.99E-18	1.48E-19	2.12E-17
Kr-85	Kr-85	1	1.05E-17	7.23E-20	8.51E-20	1.05E-17	7.23E-20	8.51E-20
Rb-87	Rb-87	1	7.32E-20	6.51E-22	0	7.32E-20	6.51E-22	0
Sr-90	Sr-90	1	1.64E-18	3.46E-21	0	1.12E-16	2.18E-19	1.65E-21
	Y-90	1	1.10E-16	2.15E-19	1.65E-21			
Zr-93	Zr-93	1	0	0	0	0	0	0
Nb-93m	Nb-93m	1	6.82E-19	3.94E-22	2.23E-18	6.82E-19	3.94E-22	2.23E-18
Nb-94	Nb-94	1	1.49E-15	4.88E-17	5.74E-17	1.49E-15	4.88E-17	5.74E-17
Mo-93	Mo-93	1	3.88E-18	2.23E-21	1.25E-17	3.88E-18	2.23E-21	1.25E-17
Tc-99	Tc-99	1	6.49E-20	5.81E-22	1.05E-22	6.49E-20	5.81E-22	1.05E-22
Ru-106	Ru-106	1	0	0	0	3.45E-16	6.66E-18	7.68E-18
	Rh-106	1	3.45E-16	6.66E-18	7.68E-18			
Ag-108m	Ag-108m	1	1.54E-15	4.83E-17	6.80E-17	1.54E-15	4.83E-17	6.8E-17
Cd-109	Cd-109	1	1.66E-17	6.55E-20	1.09E-17	1.66E-17	6.55E-20	1.09E-17

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
Cd-113m	Cd-113m	1	1.77E-18	3.23E-21	7.13E-21	1.77E-18	3.23E-21	7.13E-21
Sn-121m	Sn-121m	1	3.62E-18	7.70E-21	1.22E-18	3.69E-18	8.41E-21	1.22E-18
	Sn-121	0.776	8.86E-20	9.18E-22	0			
Sn-126	Sn-126	1	4.83E-17	6.97E-19	4.39E-18	1.97E-15	5.94E-17	7.68E-17
	Sb-126m	1	1.54E-15	4.67E-17	5.80E-17			
	Sb-126	0.14	2.71E-15	8.60E-17	1.03E-16			
Sb-125	Sb-125	1	4.08E-16	1.22E-17	1.94E-17	4.08E-16	1.22E-17	1.94E-17
Te-125m	Te-125m	1	2.68E-17	5.97E-20	8.14E-18	2.68E-17	5.97E-20	8.14E-18
I-129	I-129	1	1.96E-17	5.14E-20	4.38E-18	1.96E-17	5.14E-20	4.38E-18
Cs-134	Cs-134	1	1.48E-15	4.76E-17	5.78E-17	1.48E-15	4.76E-17	5.78E-17
Cs-135	Cs-135	1	2.69E-20	1.72E-22	0	2.69E-20	1.72E-22	0
Cs-137	Cs-137	1	2.99E-18	4.47E-21	6.11E-23	5.49E-16	1.71E-17	2.13E-17
	Ba-137m	0.944	5.78E-16	1.81E-17	2.26E-17			
Ba-133	Ba-133	1	3.73E-16	9.74E-18	1.98E-17	3.73E-16	9.74E-18	1.98E-17
La-137	La-137	1	1.97E-17	5.62E-20	3.67E-18	1.97E-17	5.62E-20	3.67E-18

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
Pm-145	Pm-145	1	2.63E-17	1.25E-19	2.91E-18	2.63E-17	1.25E-19	2.91E-18
Pm-147	Pm-147	1	2.81E-20	2.30E-22	1.79E-22	2.81E-20	2.3E-22	1.79E-22
Sm-147	Sm-147	1	0	0	0	0	0	0
Sm-151	Sm-151	1	3.55E-21	3.62E-24	3.68E-21	3.55E-21	3.62E-24	3.68E-21
Eu-152	Eu-152	1	1.07E-15	3.54E-17	4.26E-17	1.07E-15	3.54E-17	4.26E-17
Eu-154	Eu-154	1	1.17E-15	3.89E-17	4.42E-17	1.17E-15	3.89E-17	4.42E-17
Eu-155	Eu-155	1	5.35E-17	8.67E-19	2.27E-18	5.35E-17	8.67E-19	2.27E-18
Ho-163[12]	Ho-163	1	0	0	0	0	0	0
Ho-166m	Ho-166m	1	1.65E-15	5.17E-17	5.97E-17	1.65E-15	5.17E-17	5.97E-17
Hf-178n	Hf-178n	1	2.22E-15	6.47E-17	8.46E-17	2.22E-15	6.47E-17	8.46E-17
Pt-193	Pt-193	1	1.54E-19	3.38E-23	4.73E-18	1.54E-19	3.38E-23	4.73E-18
Tl-204	Tl-204	1	1.08E-17	2.08E-20	1.92E-19	1.08E-17	2.08E-20	1.92E-19
Pb-210	Pb-210	1	2.13E-18	1.06E-20	9.72E-18	3.72E-17	3.98E-20	9.72E-18
	Bi-210	1	3.51E-17	2.92E-20	1.53E-23			

[12] Ho-163 is not listed in Federal Guidance Report No. 13, but it has negligible emissions.

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
Po-210	Po-210	1	8.07E-21	2.64E-22	3.60E-22	8.07E-21	2.64E-22	3.6E-22
Ra-226	Ra-226	1	6.11E-18	1.56E-19	5.23E-19	1.69E-15	5.67E-17	6.52E-17
	Rn-222	1	3.82E-19	1.17E-20	1.50E-20			
	Po-218	1	8.64E-21	2.85E-22	0			
	Pb-214	0.9998	2.40E-16	6.65E-18	1.48E-17			
	Bi-214	1	1.44E-15	4.99E-17	4.99E-17			
	Po-214	0.9998	7.91E-20	2.59E-21	3.07E-21			
Ra-228	Ra-228	1	0	0	3.85E-18	9.38E-16	3.03E-17	4.38E-17
	Ac-228	1	9.38E-16	3.03E-17	3.99E-17			
Ac-227	Ac-227	1	1.41E-19	2.40E-21	1.01E-18	4.65E-16	9.98E-18	4.25E-17
	Th-227	0.9862	9.81E-17	2.57E-18	2.11E-17			
	Ra-223	1	1.21E-16	2.96E-18	1.32E-17			
	Rn-219	1	5.28E-17	1.53E-18	2.54E-18			
	Po-215	1	1.68E-19	5.06E-21	6.88E-21			
	Pb-211	1	9.49E-17	1.56E-18	2.60E-18			

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
	Bi-211	1	4.40E-17	1.27E-18	2.21E-18			
	Tl-207	0.9972	5.56E-17	1.23E-19	8.63E-20			
Th-228	Th-228	1	2.13E-18	3.85E-20	2.82E-18	1.44E-15	5.18E-17	5.79E-17
	Ra-224	1	9.15E-18	2.53E-19	4.96E-19			
	Rn-220	1	3.69E-19	1.15E-20	2.41E-20			
	Po-216	1	1.61E-20	5.26E-22	5.66E-22			
	Pb-212	1	1.35E-16	3.46E-18	1.09E-17			
	Bi-212	1	2.25E-16	5.96E-18	7.05E-18			
	Po-212	0.6406	0	0	0			
	Tl-208	0.3594	2.97E-15	1.17E-16	1.02E-16			
Th-229	Th-229	1	7.90E-17	1.55E-18	2.73E-17	3.44E-16	7.87E-18	4.80E-17
	Ra-225	1	1.07E-17	4.63E-20	5.14E-18			
	Ac-225	1	1.47E-17	3.09E-19	6.78E-18			
	Fr-221	1	2.84E-17	7.56E-19	1.74E-18			
	At-217	1	2.92E-19	8.86E-21	1.42E-20			

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
	Bi-213	0.9999	1.68E-16	3.83E-18	5.44E-18			
	Po-213	0.979	0	0	1.41E-21			
	Tl-209	0.0209	1.92E-15	6.56E-17	7.52E-17			
	Pb-209	0.9999	3.19E-18	4.04E-21	0			
Th-230	Th-230	1	6.37E-19	5.73E-21	2.45E-18	6.37E-19	5.73E-21	2.45E-18
Th-232	Th-232	1	4.55E-19	2.44E-21	2.26E-18	4.55E-19	2.44E-21	2.26E-18
Pa-231	Pa-231	1	3.78E-17	9.44E-19	1.66E-17	3.78E-17	9.44E-19	1.66E-17
U-232	U-232	1	8.08E-19	4.25E-21	3.04E-18	8.08E-19	4.25E-21	3.04E-18
U-233	U-233	1	6.00E-19	6.77E-21	1.56E-18	6E-19	6.77E-21	1.56E-18
U-234	U-234	1	5.86E-19	1.84E-21	2.78E-18	5.86E-19	1.84E-21	2.78E-18
U-235	U-235	1	1.40E-16	3.53E-18	1.32E-17	1.56E-16	3.70E-18	3.22E-17
	Th-231	1	1.56E-17	1.72E-19	1.90E-17			
U-236	U-236	1	5.03E-19	9.53E-22	2.53E-18	5.03E-19	9.53E-22	2.53E-18
U-238	U-238	1	4.24E-19	4.27E-22	2.04E-18	1.16E-16	6.42E-19	5.65E-18
	Th-234	1	7.50E-18	1.14E-19	2.87E-18			

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
	Pa-234m	1	1.08E-16	5.28E-19	7.37E-19			
Np-237	Np-237	1	2.52E-17	3.73E-19	1.55E-17	2.11E-16	5.41E-18	3.60E-17
	Pa-233	1	1.86E-16	5.04E-18	2.05E-17			
Pu-238	Pu-238	1	6.26E-19	6.25E-22	2.64E-18	6.26E-19	6.25E-22	2.64E-18
Pu-239	Pu-239	1	2.84E-19	1.41E-21	1.11E-18	2.84E-19	1.41E-21	1.11E-18
Pu-240	Pu-240	1	6.01E-19	6.03E-22	2.48E-18	6.01E-19	6.03E-22	2.48E-18
Pu-241	Pu-241	1	1.72E-21	2.84E-23	3.71E-22	1.72E-21	2.84E-23	3.71E-22
Pu-242	Pu-242	1	4.98E-19	5.32E-22	2.13E-18	4.98E-19	5.32E-22	2.13E-18
Pu-244[13]	Pu-244	1	0	0	3.50E-18	3.89E-16	1.02E-17	2.82E-17
	U-240	0.9988	3.20E-18	5.95E-21	6.68E-18			
	Np-240m	0.9988	3.86E-16	1.02E-17	1.80E-17			
Am-241	Am-241	1	2.33E-17	1.99E-19	9.80E-18	2.33E-17	1.99E-19	9.8E-18
Am-242m	Am-242m	1	2.26E-18	7.71E-21	5.20E-18	1.83E-17	2.48E-19	1.15E-17
	Am-242	0.9955	1.61E-17	2.41E-19	6.37E-18			

[13] Pu-244 is not listed in Federal Guidance Report No. 13, but its contribution to dose is expected to be small compared with its progeny.

Parent	Decay Chain	Branching Ratio	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Chain Surface Dose Factor (Sv/s per Bq/m^2)	Chain Slab Dose Factor (Sv/s per Bq/m^3)	Chain Point Source Air Kerma Coefficient (Gy m^2/s per Bq)
Am-243	Am-243	1	4.80E-17	6.66E-19	6.45E-18	2.02E-16	4.36E-18	2.48E-17
	Np-239	1	1.54E-16	3.69E-18	1.83E-17			
Cm-242	Cm-242	1	7.03E-19	6.89E-22	2.17E-18	7.03E-19	6.89E-22	2.17E-18
Cm-243	Cm-243	1	1.18E-16	2.86E-18	1.51E-17	1.18E-16	2.86E-18	1.51E-17
Cm-244	Cm-244	1	6.44E-19	4.80E-22	1.87E-18	6.44E-19	4.8E-22	1.87E-18
Cm-245	Cm-245	1	8.05E-17	1.64E-18	1.54E-17	8.05E-17	1.64E-18	1.54E-17
Cm-246	Cm-246	1	5.76E-19	4.44E-22	1.99E-18	5.76E-19	4.44E-22	1.99E-18
Cm-247	Cm-247	1	2.99E-16	8.85E-18	1.22E-17	3.22E-16	9.23E-18	1.56E-17
	Pu-243	1	2.27E-17	3.82E-19	3.39E-18			
Cm-248[14]	Cm-248	1	2.30E-15	8.24E-17	8.53E-17	2.30E-15	8.24E-17	8.53E-17
Cf-249	Cf-249	1	3.15E-16	9.21E-18	1.65E-17	3.15E-16	9.21E-18	1.65E-17
Cf-250	Cf-250	1	5.33E-19	4.45E-22	2.91E-18	5.33E-19	4.45E-22	2.91E-18
Cf-251	Cf-251	1	1.13E-16	2.57E-18	1.38E-17	1.13E-16	2.57E-18	1.38E-17

[14] Cm-248 is not listed in Federal Guidance Report No. 13. However, it has significant photon emissions and may be treated like Co-60.

3.4.3 Ratios of Factors

Table 6 outlines ratios of the slab dose factors to the surface dose factors and of the point dose factors to the surface dose factors, as a useful illustration of the comparative physics involved. These ratios are provided for all decay chain radionuclides rather than summing contributions from progeny in secular equilibrium. The first of these ratios is quite consistent between radionuclides. It is higher for emitters of energetic photons because they penetrate a greater thickness of slab (e.g. Na-22 and Co-60 compared with I-129). The point dose factor to surface dose factor ratio is much more variable. High values can arise where soft photons only are emitted (see, e.g., Pu-239) because these are strongly attenuated in superficial body tissues (hence reducing effective dose), which is not reflected in air kerma values.

Table 6: Ratios of Factors for All Decay Chain Radionuclides, Progeny in Secular Equilibrium Not Taken Into Account

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
H-3	0	0		0	0	
Be-10	3.41E-18	5.38E-21	0.0016	3.41E-18	0	0.0000
C-14	1.28E-20	5.90E-23	0.0046	1.28E-20	0	0.0000
Na-22	2.05E-15	6.90E-17	0.0337	2.05E-15	7.80E-17	0.0380
Al-26	2.47E-15	8.84E-17	0.0358	2.47E-15	8.87E-17	0.0359
Cl-36	1.12E-17	1.33E-20	0.0012	1.12E-17	5.38E-21	0.0005
Ar-39	2.53E-18	4.30E-21	0.0017	2.53E-18	0	0.0000
K-40	2.03E-16	5.33E-18	0.0263	2.03E-16	5.15E-18	0.0254
Ca-41	0	0		0	0	
Fe-55	0	0		0	4.93E-27	
Co-60	2.30E-15	8.24E-17	0.0358	2.30E-15	8.53E-17	0.0371
Ni-59	0	0		0	5.88E-22	
Ni-63	0	0		0	0	
Se-79	1.65E-20	8.21E-23	0.0050	1.65E-20	0	0.0000
Kr-81	5.99E-18	1.48E-19	0.0247	5.99E-18	2.12E-17	3.5392
Kr-85	1.05E-17	7.23E-20	0.0069	1.05E-17	8.51E-20	0.0081
Rb-87	7.32E-20	6.51E-22	0.0089	7.32E-20	0	0.0000

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
Sr-90	1.64E-18	3.46E-21	0.0021	1.64E-18	0	0.0000
Y-90	1.10E-16	2.15E-19	0.0020	1.10E-16	1.65E-21	0.0000
Zr-93	0	0		0	0	
Nb-93m	6.82E-19	3.94E-22	0.0006	6.82E-19	2.23E-18	3.2698
Nb-94	1.49E-15	4.88E-17	0.0328	1.49E-15	5.74E-17	0.0385
Mo-93	3.88E-18	2.23E-21	0.0006	3.88E-18	1.25E-17	3.2216
Tc-99	6.49E-20	5.81E-22	0.0090	6.49E-20	1.05E-22	0.0016
Ru-106	0	0		0	0	
Rh-106	3.45E-16	6.66E-18	0.0193	3.45E-16	7.68E-18	0.0223
Ag-108m	1.54E-15	4.83E-17	0.0314	1.54E-15	6.80E-17	0.0442
Cd-109	1.66E-17	6.55E-20	0.0039	1.66E-17	1.09E-17	0.6566
Cd-113m	1.77E-18	3.23E-21	0.0018	1.77E-18	7.13E-21	0.0040
Sn-121m	3.62E-18	7.70E-21	0.0021	3.62E-18	1.22E-18	0.3370
Sn-121	8.86E-20	9.18E-22	0.0104	8.86E-20	0	0.0000
Sn-126	4.83E-17	6.97E-19	0.0144	4.83E-17	4.39E-18	0.0909
Sb-126m	1.54E-15	4.67E-17	0.0303	1.54E-15	5.80E-17	0.0377
Sb-126	2.71E-15	8.60E-17	0.0317	2.71E-15	1.03E-16	0.0380
Sb-125	4.08E-16	1.22E-17	0.0299	4.08E-16	1.94E-17	0.0475
Te-125m	2.68E-17	5.97E-20	0.0022	2.68E-17	8.14E-18	0.3037
I-129	1.96E-17	5.14E-20	0.0026	1.96E-17	4.38E-18	0.2235
Cs-134	1.48E-15	4.76E-17	0.0322	1.48E-15	5.78E-17	0.0391
Cs-135	2.69E-20	1.72E-22	0.0064	2.69E-20	0	0.0000
Cs-137	2.99E-18	4.47E-21	0.0015	2.99E-18	6.11E-23	0.0000
Ba-137m	5.78E-16	1.81E-17	0.0313	5.78E-16	2.26E-17	0.0391
Ba-133	3.73E-16	9.74E-18	0.0261	3.73E-16	1.98E-17	0.0531
La-137	1.97E-17	5.62E-20	0.0029	1.97E-17	3.67E-18	0.1863

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
Pm-145	2.63E-17	1.25E-19	0.0048	2.63E-17	2.91E-18	0.1106
Pm-147	2.81E-20	2.30E-22	0.0082	2.81E-20	1.79E-22	0.0064
Sm-147	0	0		0	0	
Sm-151	3.55E-21	3.62E-24	0.0010	3.55E-21	3.68E-21	1.0366
Eu-152	1.07E-15	3.54E-17	0.0331	1.07E-15	4.26E-17	0.0398
Eu-154	1.17E-15	3.89E-17	0.0332	1.17E-15	4.42E-17	0.0378
Eu-155	5.35E-17	8.67E-19	0.0162	5.35E-17	2.27E-18	0.0424
Ho-163	0	0		0	0	
Ho-166m	1.65E-15	5.17E-17	0.0313	1.65E-15	5.97E-17	0.0362
Hf-178n	2.22E-15	6.47E-17	0.0291	2.22E-15	8.46E-17	0.0381
Pt-193	1.54E-19	3.38E-23	0.0002	1.54E-19	4.73E-18	30.7143
Tl-204	1.08E-17	2.08E-20	0.0019	1.08E-17	1.92E-19	0.0178
Pb-210	2.13E-18	1.06E-20	0.0050	2.13E-18	9.72E-18	4.5634
Bi-210	3.51E-17	2.92E-20	0.0008	3.51E-17	1.53E-23	0.0000
Po-210	8.07E-21	2.64E-22	0.0327	8.07E-21	3.60E-22	0.0446
Ra-226	6.11E-18	1.56E-19	0.0255	6.11E-18	5.23E-19	0.0856
Rn-222	3.82E-19	1.17E-20	0.0306	3.82E-19	1.50E-20	0.0393
Po-218	8.64E-21	2.85E-22	0.0330	8.64E-21	0	0.0000
Pb-214	2.40E-16	6.65E-18	0.0277	2.40E-16	1.48E-17	0.0617
Bi-214	1.44E-15	4.99E-17	0.0347	1.44E-15	4.99E-17	0.0347
Po-214	7.91E-20	2.59E-21	0.0327	7.91E-20	3.07E-21	0.0388
Ra-228	0	0		0	3.85E-18	
Ac-228	9.38E-16	3.03E-17	0.0323	9.38E-16	3.99E-17	0.0425
Ac-227	1.41E-19	2.40E-21	0.0170	1.41E-19	1.01E-18	7.1631
Th-227	9.81E-17	2.57E-18	0.0262	9.81E-17	2.11E-17	0.2151
Ra-223	1.21E-16	2.96E-18	0.0245	1.21E-16	1.32E-17	0.1091

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
Rn-219	5.28E-17	1.53E-18	0.0290	5.28E-17	2.54E-18	0.0481
Po-215	1.68E-19	5.06E-21	0.0301	1.68E-19	6.88E-21	0.0410
Pb-211	9.49E-17	1.56E-18	0.0164	9.49E-17	2.60E-18	0.0274
Bi-211	4.40E-17	1.27E-18	0.0289	4.40E-17	2.21E-18	0.0502
Tl-207	5.56E-17	1.23E-19	0.0022	5.56E-17	8.63E-20	0.0016
Th-228	2.13E-18	3.85E-20	0.0181	2.13E-18	2.82E-18	1.3239
Ra-224	9.15E-18	2.53E-19	0.0277	9.15E-18	4.96E-19	0.0542
Rn-220	3.69E-19	1.15E-20	0.0312	3.69E-19	2.41E-20	0.0653
Po-216	1.61E-20	5.26E-22	0.0327	1.61E-20	5.66E-22	0.0352
Pb-212	1.35E-16	3.46E-18	0.0256	1.35E-16	1.09E-17	0.0807
Bi-212	2.25E-16	5.96E-18	0.0265	2.25E-16	7.05E-18	0.0313
Po-212	0	0		0	0	
Tl-208	2.97E-15	1.17E-16	0.0394	2.97E-15	1.02E-16	0.0343
Th-229	7.90E-17	1.55E-18	0.0196	7.90E-17	2.73E-17	0.3456
Ra-225	1.07E-17	4.63E-20	0.0043	1.07E-17	5.14E-18	0.4804
Ac-225	1.47E-17	3.09E-19	0.0210	1.47E-17	6.78E-18	0.4612
Fr-221	2.84E-17	7.56E-19	0.0266	2.84E-17	1.74E-18	0.0613
At-217	2.92E-19	8.86E-21	0.0303	2.92E-19	1.42E-20	0.0486
Bi-213	1.68E-16	3.83E-18	0.0228	1.68E-16	5.44E-18	0.0324
Po-213	0	0		0	1.41E-21	
Tl-209	1.92E-15	6.56E-17	0.0342	1.92E-15	7.52E-17	0.0392
Pb-209	3.19E-18	4.04E-21	0.0013	3.19E-18	0	0.0000
Th-230	6.37E-19	5.73E-21	0.0090	6.37E-19	2.45E-18	3.8462
Th-232	4.55E-19	2.44E-21	0.0054	4.55E-19	2.26E-18	4.9670
Pa-231	3.78E-17	9.44E-19	0.0250	3.78E-17	1.66E-17	0.4392
U-232	8.08E-19	4.25E-21	0.0053	8.08E-19	3.04E-18	3.7624

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
U-233	6.00E-19	6.77E-21	0.0113	6.00E-19	1.56E-18	2.6000
U-234	5.86E-19	1.84E-21	0.0031	5.86E-19	2.78E-18	4.7440
U-235	1.40E-16	3.53E-18	0.0252	1.40E-16	1.32E-17	0.0943
Th-231	1.56E-17	1.72E-19	0.0110	1.56E-17	1.90E-17	1.2179
U-236	5.03E-19	9.53E-22	0.0019	5.03E-19	2.53E-18	5.0298
U-238	4.24E-19	4.27E-22	0.0010	4.24E-19	2.04E-18	4.8113
Th-234	7.50E-18	1.14E-19	0.0152	7.50E-18	2.87E-18	0.3827
Pa-234m	1.08E-16	5.28E-19	0.0049	1.08E-16	7.37E-19	0.0068
Np-237	2.52E-17	3.73E-19	0.0148	2.52E-17	1.55E-17	0.6151
Pa-233	1.86E-16	5.04E-18	0.0271	1.86E-16	2.05E-17	0.1102
Pu-238	6.26E-19	6.25E-22	0.0010	6.26E-19	2.64E-18	4.2173
Pu-239	2.84E-19	1.41E-21	0.0050	2.84E-19	1.11E-18	3.9085
Pu-240	6.01E-19	6.03E-22	0.0010	6.01E-19	2.48E-18	4.1265
Pu-241	1.72E-21	2.84E-23	0.0165	1.72E-21	3.71E-22	0.2157
Pu-242	4.98E-19	5.32E-22	0.0011	4.98E-19	2.13E-18	4.2771
Pu-244	0	0		0	3.50E-18	
U-240	3.20E-18	5.95E-21	0.0019	3.20E-18	6.68E-18	2.0875
Np-240m	3.86E-16	1.02E-17	0.0264	3.86E-16	1.80E-17	0.0466
Am-241	2.33E-17	1.99E-19	0.0085	2.33E-17	9.80E-18	0.4206
Am-242m	2.26E-18	7.71E-21	0.0034	2.26E-18	5.20E-18	2.3009
Am-242	1.61E-17	2.41E-19	0.0150	1.61E-17	6.37E-18	0.3957
Am-243	4.80E-17	6.66E-19	0.0139	4.80E-17	6.45E-18	0.1344
Np-239	1.54E-16	3.69E-18	0.0240	1.54E-16	1.83E-17	0.1188
Cm-242	7.03E-19	6.89E-22	0.0010	7.03E-19	2.17E-18	3.0868
Cm-243	1.18E-16	2.86E-18	0.0242	1.18E-16	1.51E-17	0.1280
Cm-244	6.44E-19	4.80E-22	0.0007	6.44E-19	1.87E-18	2.9037

Radio-nuclide	Surface Dose Factor (Sv/s per Bq/m^2)	Slab Dose Factor (Sv/s per Bq/m^3)	Ratio, Slab: Surface	Surface Dose Factor (Sv/s per Bq/m^2)	Point Source Air Kerma Coefficient (Gy m^2/s per Bq)	Ratio, Point: Surface
Cm-245	8.05E-17	1.64E-18	0.0204	8.05E-17	1.54E-17	0.1913
Cm-246	5.76E-19	4.44E-22	0.0008	5.76E-19	1.99E-18	3.4549
Cm-247	2.99E-16	8.85E-18	0.0296	2.99E-16	1.22E-17	0.0408
Pu-243	2.27E-17	3.82E-19	0.0168	2.27E-17	3.39E-18	0.1493
Cm-248	2.30E-15	8.24E-17	0.0358	2.30E-15	8.53E-17	0.0371
Cf-249	3.15E-16	9.21E-18	0.0292	3.15E-16	1.65E-17	0.0524
Cf-250	5.33E-19	4.45E-22	0.0008	5.33E-19	2.91E-18	5.4597
Cf-251	1.13E-16	2.57E-18	0.0227	1.13E-16	1.38E-17	0.1221

3.4.4 Effective Dose Rates for Exposure from Surface or Volume Contaminated Spheres

Effective dose rates for exposure from surface or volume contaminated spheres are not presented here. However, the approach by which they may be calculated is presented in Appendix B. The key parameters relevant in calculating dose rates include:

- the ratio of the radius of the sphere to distance from the centre of the sphere to the point of exposure (volume-contaminated spheres) or from the surface of the sphere (surface-contaminated spheres);
- the photon flux derived from the activity density;
- the effective dose per unit air kerma for photons of the relevant energy;
- the density of the volume source;[15]
- whether for surface contamination, sources are sorbing or non-sorbing.

Appendix C provides the information necessary to calculate effective doses including scaling factors for different sphere sizes and exposure distances.

3.4.5 Effective Dose Rates for Exposure from Small Sealed Sources

Effective dose rates from small sealed sources include both photon and beta contributions are given in Table 7; additional background information is provided in Appendix E. Values are given only for those radionuclides that are likely to be present in significant numbers of sealed sources, including their daughters.

[15] For 'standard' dose calculations the volume source material is usually assumed to be concrete.

Table 7: Dose Rates from Small Sealed Sources

Parent	Decay Chain	Branching Ratio	Dose Factor*	Photon Dose Factor for Chain	Mean Beta Energy (MeV per transformation)	Phi Value	Beta Dose Factor**	Beta Dose Factor for Chain
H-3	H-3	1	0	0.00E+00	0.0057	0.2750	6.004E-16	6.00E-16
C-14	C-14	1	0	0.00E+00	0.0494	0.2260	4.276E-15	4.28E-15
Cl-36	Cl-36	1	5.38E-21	5.38E-21	0.2732	0.0489	5.117E-15	5.12E-15
Co-60	Co-60	1	8.53E-17	8.53E-17	0.0969	0.170	6.31E-15	6.31E-15
Ni-63	Ni-63	1	0	0.00E+00	0.0174	0.2620	1.746E-15	1.75E-15
Sr-90	Sr-90	1	0.00E+00	1.65E-21	0.1957	0.060	4.50E-15	1.03E-14
	Y-90	1	1.65E-21		0.9331	0.016	5.83E-15	
Cs-137	Cs-137	1	6.11E-23	2.13E-17	0.1884	0.063	4.53E-15	6.39E-15
	Ba-137m	0.944	2.26E-17		0.0653	0.0788	1.97E-15	
Pb-210	Pb-210	1	9.72E-18	9.72E-18	0.0404	0.2360	3.65E-15	8.97E-15
	Bi-210	1	1.53E-23		0.3889	0.0357	5.32E-15	
	Po-210	1	3.60E-22		0	0.0000	0.00E+00	
Ra-226	Ra-226	1	5.23E-19	6.52E-17	0.0039	0.2770	4.14E-16	1.15E-14
	Rn-222	1	1.50E-20		0	0.0000	0.00E+00	
	Po-218	1	0.00E+00		0	0.0000	0.00E+00	
	Pb-214	1	1.48E-17		0.2948	0.0458	5.17E-15	
	Bi-214	1	4.99E-17		0.6631	0.0232	5.89E-15	
	Po-214	1	3.07E-21		0	0.0000	0.00E+00	
Ra-228	Ra-228	1	3.85E-18	4.38E-17	0.0132	0.2660	1.34E-15	7.02E-15
	Ac-228	1	3.99E-17		0.4494	0.0330	5.68E-15	
Th-228	Th-228	1	2.82E-18	5.79E-17	0.021	0.2580	2.08E-15	1.55E-14
	Ra-224	1	4.96E-19		0.0023	0.2780	2.45E-16	
	Rn-220	1	2.41E-20		0	0.0000	0.00E+00	
	Po-216	1	5.66E-22		0	0.0000	0.00E+00	
	Pb-212	1	1.09E-17		0.1766	0.0766	5.18E-15	

Parent	Decay Chain	Branching Ratio	Dose Factor*	Photon Dose Factor for Chain	Mean Beta Energy (MeV per transformation)	Phi Value	Beta Dose Factor**	Beta Dose Factor for Chain
	Bi-212	1	7.05E-18		0.5046	0.0304	5.88E-15	
	Po-212	0.6407	0.00E+00		0	0.0000	0.00E+00	
	Tl-208	0.3593	1.02E-16		0.6113	0.0256	5.99E-15	
Th-232	Th-232	1	2.26E-18	2.26E-18	0.0126	0.2670	1.29E-15	1.29E-15
Np-237	Np-237	1	1.55E-17	3.60E-17	0.0681	0.2040	5.321E-15	1.00E-14
	Pa-233	1	2.05E-17		0.215	0.0573	4.718E-15	
Pu-239	Pu-239	1	1.11E-18	1.11E-18	0.0074	0.2730	7.737E-16	7.74E-16
Am-241	Am-241	1	9.80E-18	9.80E-18	0.0373	0.2390	3.41E-15	3.41E-15

*Gy m^2 per Bq s from ICRP Publication 107, **Gy m^2 per Bq s

4 Common Radionuclide-independent Data

The data below are default values for common radionuclide independent assessment data. While a wide range of such data is relevant, a subset specifically identified as being of relevance to the ESC are provided. These may need to be amended for specific potential exposure group (PEG) and exposure circumstances.

4.1 Suspended air concentration, relevant to estimating impacts due to inhalation of soil and sediment

For a simple mass loading model that assumes all dust in air at a location comes from the contaminated area, and the activity concentration in the resuspended dust equals that in the contaminated source, a generic air suspended soil concentration is taken as **1E-7 kg m^{-3}** (although values ranging from 5E-9 to 5E-5 kg m^{-3} have been observed and may need to be considered in sensitivity studies (Wasiolek *et al.*, 2005)). This mass loading will increase dramatically during soil disturbance, with any value above 1.5E-07 constituting a nuisance dust problem (NCRP, 1999). However for individuals present at the areas of interest, a limited amount of human-induced disturbance of the substrate may be anticipated, so although cautious, the mass load in air of 1E-7 kg m^{-3} is a reasonable reference basis for calculations (Thorne 2009, p47).

PEG-specific inhalation rates can be calculated by multiplying this factor by the breathing rate and average occupancy.

4.2 Breathing rates

For moderately energetic activities undertaken by adults in the various areas, the breathing rate at light exercise is taken as the arithmetic average of the male and female values, **1.375 m^3 h^{-1} / 12050 m^3 y^{-1}** (Table 8 of ICRP, 1994 and Table 24 of Thorne, 2009 respectively).

4.3 Inadvertent ingestion of soil and sediment

The hourly inadvertent ingestion rate for an adult occupying relevant locations is given as **5 mg h^{-1}** (Thorne 2010, Table 8). For PEG-specific ingestion rates, average occupancy requires to be taken into account. Note that the hourly rate applies to contexts in which significant inadvertent ingestion is more likely to occur. Thus, long-term average rates will typically be rather lower than the hourly rates adopted.

4.4 Water intake (humans)

Daily fluid consumption for adults is taken as **1.64 L d^{-1}** based upon 0.045-0.73 L d^{-1} of tap water, 0.32-1.45 L d^{-1} water-based drinks, and 1 L y^{-1} inadvertent ingestion during swimming assuming that ~ 0.02 L are swallowed on each occasion on a few tens of occasions per year.

5 References

ICRP, 1983. ICRP Publication 38: Radionuclide Transformations: Energy and Intensity of Emissions, Annals of the ICRP, **11-13.**

ICRP, 1996. ICRP Publication 72: Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5: Compilation of Ingestion and Inhalation Dose Coefficients, Annals of the ICRP, **26(1)**

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USEPA, 2002. Federal Guidance Report 13, Cancer Risk Coefficients for Environmental Exposure to Radionuclides: CD Supplement, EPA-402-C-99-001, Rev. 1, US Environmental Protection Agency, Washington, DC.

Appendix A: Alphabetical Radionuclide List

The list of all radionuclides present in the LLWR inventory as identified in the main body of this report, is repeated below, ordered alphabetically. As noted in Section 2, the list presents radionuclides present in the Trench, Vault 8 and Future Vault inventory estimates, using Inventory Case 2 for future disposals (Serco, 2010).

Ac-227, Ag-108m, Al-26, Am-241, Am-242m, Am-243, Ar-39, Ba-133, Be-10, C-14, Ca-41, Cd-109, Cd-113m, Cf-249, Cf-250, Cf-251,, 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, Fe-55, H-3, Hf-178n, Ho-163, Ho-166m, I-129, K-40, Kr-81, Kr-85, La-137, Mo-93, Na-22, Nb-93m, Nb-94, Ni-59, Ni-63, Np-237, Pa-231, Pb-210, Pm-145, Pm-147, Po-210, Pt-193, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, Pu-244, Ra-226, Ra-228, Rb-87, Ru-106, Sb-125, Se-79, Sm-147, Sm-151, Sn-121m, Sn-126, Sr-90, Tc-99, Te-125m, Th-228, Th-229, Th-230, Th-232, Tl-204, U-232, U-233, U-234, U-235, U-236, U-238, Zr-93

Appendix A Reference

Serco, 2010. ESC 2011: The disposed and forward inventory of LLWR, SERCO/E003756/12. Issue 1.

Appendix B: Calculation of Dose Factors for Surface or Volume Contaminated Spheres

B1 Theoretical Basis for Dose Rate Calculations for Spheres

For assessing the effective dose rate from contaminated objects, there is a requirement to assess the effective dose rate from spherical surface-contaminated and volume-contaminated objects. There are convenient analytical formulae to estimate photon fluxes from such objects and these have been summarised by Ezure (2002).

B1.1 Spherical Surface Source

The flux at a distance from the centre of a slab-shielded spherical surface source that contains a uniform absorbent medium is given by:

$$\varphi = S_a G_s(a/R, \mu_s R, \mu t)/2$$

where φ (m^{-2} s^{-1}) is the flux;

S_a (m^{-2} s^{-1}) is the surface source strength;

G_s is the attenuation function tabulated by Ezure (2002);

a (m) is the distance from the centre of the sphere at which the flux is estimated;

R (m) is the radius of the sphere;

μ_s (m^{-1}) is the attenuation coefficient for the material of the sphere;

μ (m^{-1}) is the attenuation coefficient for the slab shield;

t (m) is the thickness of the slab shield.

In the current application, no slab shield is interposed between the source and the exposed individual, so the fundamental equation reduces to:

$$\varphi = S_a G_s(a/R, \mu_s R, 0)/2$$

Values of $G_s(a/R, \mu_s R, 0)$ are listed in Table B1.

Table B1: Values of $G_s(a/R, \mu_s R, 0)$ for a Surface-contaminated Sphere

	$\mu_s R$					
a*/*R	**0**	**1**	**3**	**5**	**10**	**20**
1.25	1.75600	1.29000	1.05200	0.98410	0.93300	0.90460
1.5	1.07300	0.77920	0.63390	0.59510	0.56470	0.54960
2	0.54750	0.39480	0.32240	0.30290	0.28940	0.28160
3	0.23160	0.16570	0.13560	0.12750	0.12150	0.11830
5	0.08103	0.05790	0.04729	0.04463	0.04259	0.04167
10	0.02011	0.01436	0.01165	0.01109	0.01053	0.01028

As can be seen from Table B1, the main cause of variation is the value of a/R. This is as expected, since much of the flux comes from the forward hemisphere of the sphere and does not pass through the internal attenuating medium.

Also, if the source were a point rather than a spherical volume, the flux would be expected to diminish as $1/a^2$. Therefore, it seems reasonable to reduce the variation with a/R by introducing a new function:

$H_s = G_s(a/R)^2$

$\varphi = (R/a)^2 S_a H_s(a/R, \mu_s R, 0)/2$

Values of H_s are given in Table B2.

Table B2: Values of $H_s(a/R, \mu_s R, 0)$ for a Surface-contaminated Sphere

	$\mu_s R$					
a*/*R	**0**	**1**	**3**	**5**	**10**	**20**
1.25	2.74	2.02	1.64	1.54	1.46	1.41
1.5	2.41	1.75	1.43	1.34	1.27	1.24
2	2.19	1.58	1.29	1.21	1.16	1.13
3	2.08	1.49	1.22	1.15	1.09	1.06
5	2.03	1.45	1.18	1.12	1.06	1.04
10	2.01	1.44	1.17	1.11	1.05	1.03

If $R \rightarrow \infty$, and $a/R \rightarrow 1$ this corresponds to a point just above an infinite plane. Thus, the value obtained for $a/R = 1.25$ and $\mu_s R = 20$ should be a good approximation to a thin planar source located on the upper surface of an infinite flat plane (extrapolation of the value of H_s to $a/R = 1.0$ suggests that 1.6 would be a better approximation than 1.41). As dose rate is proportional to photon flux at any photon energy, but with the constant of proportionality varying with photon energy:

$E = E_{plane}(H_s/1.6)\,(R/a)^2/2 \qquad = E_{plane}(H_s/3.2)\,(R/a)^2$

where E (Sv h^{-1} per Bq m^{-2}) is the effective dose rate from a surface-contaminated sphere of radius R (m) to an individual located at a distance a (m) from its centre; and

E_{plane} (Sv h^{-1} per Bq m^{-2}) is the effective dose rate from an extended plane source.

B1.2 Spherical Volume Source

In the case of a spherical volume source, the relevant equation is:

$$\varphi = S_v R G_v(a/R, \mu_s R, \mu t)/\pi$$

where S_v (m^{-3} s^{-1}) is the specific strength of the volume source and G_v is the volumetric equivalent of G_s. Note that a factor of π rather than 2 arises in the denominator in this case. Again, the relevant reduced equation is:

$$\varphi = S_v R G_v(a/R, \mu_s R, 0)/\pi$$

Relevant values of $G_v(a/R, \mu_s R, 0)$ are listed in Table B3.

Table B3: Values of $G_v(a/R, \mu_s R, 0)$ for a Volume-contaminated Sphere

	$\mu_s R$						
a/R	**0**	**1**	**2**	**4**	**8**	**10**	**15**
1	1.571E+00	8.867E-01	5.975E-01	3.392E-01	1.865E-01	1.492E-01	9.807E-02
1.25	7.934E-01	4.284E-01	2.734E-01	1.506E-01	7.771E-02	6.273E-02	4.164E-02
1.5	5.176E-01	2.769E-01	1.755E-01	9.655E-02	4.979E-02	3.981E-02	2.665E-02
2	2.760E-01	1.468E-01	9.270E-02	5.094E-02	2.613E-02	2.089E-02	1.402E-02
3	1.188E-01	6.301E-02	3.961E-02	2.175E-02	1.114E-02	8.926E-03	5.989E-03
5	4.223E-02	2.222E-02	1.407E-02	7.666E-03	3.939E-03	3.150E-03	2.109E-03
10	1.046E-02	5.541E-03	3.486E-03	1.905E-03	9.760E-04	7.826E-04	5.238E-04

As in the case of the surface-contaminated sphere, it is convenient to introduce:

$$H_v = G_v(a/R)^2$$

$$\varphi = R(R/a)^2 S_v H_v(a/R, \mu_s R, 0)/\pi$$

Values of H_v are given in Table B4.

Table B4: Values of $H_v(a/R, \mu_s R, 0)$ for a Volume-contaminated Sphere

	$\mu_s R$						
a*/*R	**0**	**1**	**2**	**4**	**8**	**10**	**15**
1	1.571	0.887	0.598	0.339	0.187	0.149	0.098
1.25	1.240	0.669	0.427	0.235	0.121	0.098	0.065
1.5	1.165	0.623	0.395	0.217	0.112	0.090	0.060
2	1.104	0.587	0.371	0.204	0.105	0.084	0.056
3	1.069	0.567	0.356	0.196	0.100	0.080	0.054
5	1.056	0.556	0.352	0.192	0.098	0.079	0.053
10	1.046	0.554	0.349	0.191	0.098	0.078	0.052

Again, this removes much of the dependence on a/R. In this case, the appropriate comparison is with a semi-infinite slab source. Again $a/R \rightarrow 1$ and $R \rightarrow \infty$. Inspection of Table B4 shows that $\mu_s R$ cannot be used to approximate $R \rightarrow \infty$. This is well seen graphically in Figure B1.

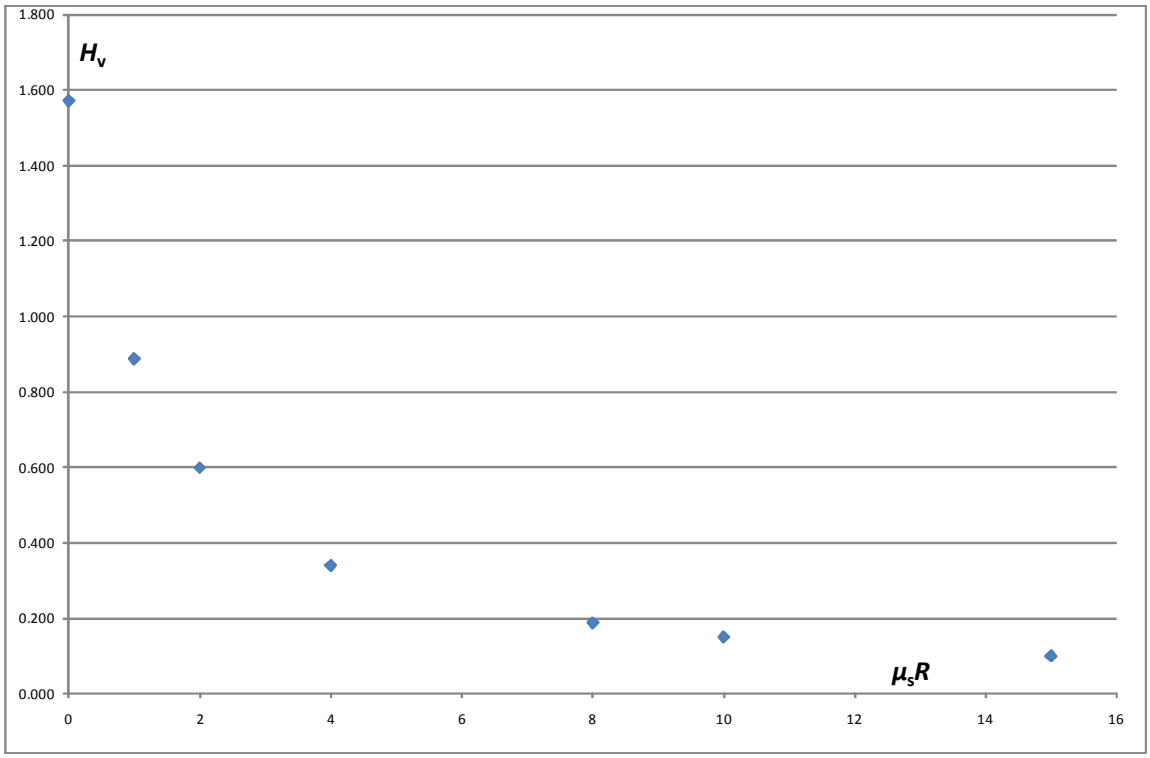

Figure B1: Relationship of H_v to $\mu_s R$ for a/R = 1.0

An inverse relationship with $\mu_s R$ is apparent. The product $H_v\ \mu_s R$ appears to converge to approximately 1.48. This is as expected. For fixed R, the thickness of the layer on the surface of the sphere from which photons can escape decreases as μ increases. This demonstrates that there is a fundamental difficulty in relating the results to those for a semi-infinite slab source, i.e. a specific choice of μ has to be made.

Thus, the results given in Table B4 have to be used more directly (see Section B3).

B2 Surface-Source Calculations

As noted in Section C1.1, the key equation is:

$E = E_{plane}(H_s/3.2)\ (R/a)^2$

The only term in this equation that is dependent upon the photon emissions of a specific radionuclide is E_{plane}. The scaling factor $(H_s/3.2)\ (R/a)^2$ depends upon R/a and implicitly through H_s on $\mu_s R$. However, examination of Table B2 shows that only a weak (factor of two) dependence on $\mu_s R$ exists. The factor of two exists because with $\mu_s R$ small both the front and back hemispheres of the sphere are effective in irradiating the exposed individual, whereas with $\mu_s R$ large only the front hemisphere is effective. Taking into account this weak dependence, only two cases are simulated. These are the no absorption case and the strong absorption case. These are characterised by $\mu_s R$ = 0 and 20, respectively.

Also, it is more convenient to think in terms of the distance of an individual from the surface of the sphere, x (m), than the distance from its centre. Thus, R/a is rewritten as $R/(R+x)$. The relevant calculations of $(H_s/3.2)\ (R/a)^2$ are shown in Table B5.

Table B5: Computation of Scale Factors for Surface Sources

Distance from Source (m)	Non-sorbing Source (R in m)							
$(R/a)^2$	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2.0**
0.3	6.25E-02	1.60E-01	3.27E-01	4.44E-01	5.29E-01	5.92E-01	6.94E-01	7.56E-01
1.0	8.26E-03	2.78E-02	8.16E-02	1.41E-01	1.98E-01	2.50E-01	3.60E-01	4.44E-01
3.0	1.04E-03	3.91E-03	1.38E-02	2.78E-02	4.43E-02	6.25E-02	1.11E-01	1.60E-01
a/R	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	4.00	2.50	1.75	1.50	1.38	1.30	1.20	1.15
1.0	11.00	6.00	3.50	2.67	2.25	2.00	1.67	1.50
3.0	31.00	16.00	8.50	6.00	4.75	4.00	3.00	2.50
H_s	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	2.05	2.13	2.30	2.41	2.58	2.68	2.79	2.87
1.0	2.00	2.02	2.07	2.12	2.16	2.19	2.34	2.41
3.0	2.00	2.00	2.01	2.02	2.03	2.05	2.08	2.13
Scale Factor	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	4.00E-02	1.07E-01	2.35E-01	3.35E-01	4.26E-01	4.96E-01	6.05E-01	6.78E-01
1.0	5.17E-03	1.75E-02	5.28E-02	9.32E-02	1.33E-01	1.71E-01	2.63E-01	3.35E-01
3.0	6.50E-04	2.44E-03	8.69E-03	1.75E-02	2.81E-02	4.00E-02	7.22E-02	1.07E-01

Distance from Source (m)	Sorbing Source (R in m)							
$(R/a)^2$	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	6.25E-02	1.60E-01	3.27E-01	4.44E-01	5.29E-01	5.92E-01	6.94E-01	7.56E-01

1.0	8.26E-03	2.78E-02	8.16E-02	1.41E-01	1.98E-01	2.50E-01	3.60E-01	4.44E-01
3.0	1.04E-03	3.91E-03	1.38E-02	2.78E-02	4.43E-02	6.25E-02	1.11E-01	1.60E-01
a/R	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	4.00	2.50	1.75	1.50	1.38	1.30	1.20	1.15
1.0	11.00	6.00	3.50	2.67	2.25	2.00	1.67	1.50
3.0	31.00	16.00	8.50	6.00	4.75	4.00	3.00	2.50
H_s	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	1.05	1.10	1.19	1.24	1.33	1.38	1.44	1.48
1.0	1.03	1.04	1.05	1.08	1.11	1.13	1.20	1.24
3.0	1.03	1.03	1.03	1.04	1.04	1.05	1.06	1.10
Scale Factor	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	2.05E-02	5.50E-02	1.21E-01	1.72E-01	2.20E-01	2.55E-01	3.13E-01	3.50E-01
1.0	2.66E-03	9.03E-03	2.68E-02	4.75E-02	6.85E-02	8.83E-02	1.35E-01	1.72E-01
3.0	3.35E-04	1.26E-03	4.46E-03	9.03E-03	1.44E-02	2.05E-02	3.68E-02	5.50E-02

These scale factors are multiplied by the dose factors for an infinite surface source given in Table 3 of the main text.

B3 Volume Source Calculations

In this case, the fundamental equation to obtain the photon flux is:

$$\varphi = R(R/a)^2 S_v H_v(a/R, \mu_s R, 0)/\pi$$

where S_v (s^{-1} m^{-3}) is the specific strength of the volume source and φ (m^{-2} s^{-1}) is the flux.

The only quantity in this expression that depends on the characteristics of the photon emissions of a radionuclide is H_v. Values of H_v are given in Table B4. However, these values are only for specific values of a/R and $\mu_s R$. It is more convenient to have H_v expressed as a continuous function of these quantities. By trial and error a suitable function was found to be:

$$H_v = \{1.0 + 0.86/(a/R)^{1.8}\}\{\exp(-[\mu_s R]^{0.4}\}$$

Calculations made using this function, in comparison with the results shown in Table B4, are listed in Table B6.

Table B6: Accuracy of an Analytical Formula for Estimating H_v

Calculated	***μR***						
a/R	**0**	**1**	**2**	**4**	**8**	**10**	**15**
1	1.864	0.687	0.499	0.328	0.188	0.152	0.098
1.25	1.578	0.581	0.423	0.277	0.159	0.128	0.083
1.5	1.417	0.522	0.379	0.249	0.143	0.115	0.074
2	1.248	0.460	0.334	0.219	0.126	0.102	0.065
3	1.120	0.412	0.300	0.197	0.113	0.091	0.059
5	1.048	0.386	0.281	0.184	0.106	0.085	0.055
10	1.014	0.373	0.271	0.178	0.102	0.083	0.053
Table B4	***μR***						
a/R	**0**	**1**	**2**	**4**	**8**	**10**	**15**
1	1.571	0.887	0.598	0.339	0.187	0.149	0.098
1.25	1.24	0.669	0.427	0.235	0.121	0.098	0.065
1.5	1.165	0.623	0.395	0.217	0.112	0.09	0.06
2	1.104	0.587	0.371	0.204	0.105	0.084	0.056
3	1.069	0.567	0.356	0.196	0.1	0.08	0.054
5	1.056	0.556	0.352	0.192	0.098	0.079	0.053
10	1.046	0.554	0.349	0.191	0.098	0.078	0.052
Ratio	***μR***						
a/R	**0**	**1**	**2**	**4**	**8**	**10**	**15**
1	0.84	1.29	1.20	1.03	0.99	0.98	1.00
1.25	0.79	1.15	1.01	0.85	0.76	0.76	0.79
1.5	0.82	1.19	1.04	0.87	0.78	0.78	0.81
2	0.88	1.28	1.11	0.93	0.83	0.83	0.86
3	0.95	1.37	1.19	1.00	0.89	0.88	0.92
5	1.01	1.44	1.25	1.04	0.93	0.93	0.97
10	1.03	1.48	1.29	1.07	0.96	0.95	0.98

Values range from 0.052 to 1.571, but the ratio of the calculated to the Table B4 value lies in the range 0.76 to 1.29 demonstrating the adequacy of the analytical equation and the level of accuracy required for the calculations undertaken here (bearing in mind the much greater variability arising from differences in the size, composition and geometry of the volume sources considered).

In this case, there is a strong dependence on the value of μR, so specific consideration has to be given to this quantity. Variations of the flux and energy mass absorption coefficients are given by Hubble and Seltzer (1996). The values for ordinary concrete are taken as being most appropriate to represent waste blocks and are illustrated in Figure B2.

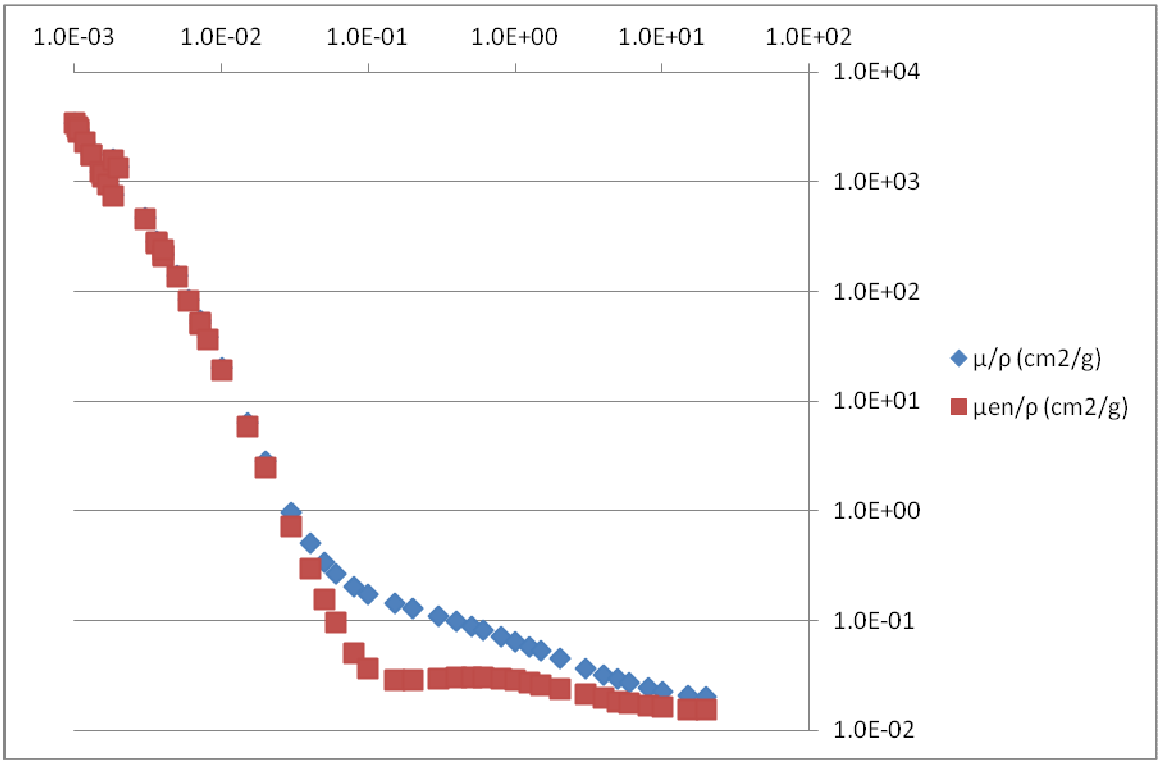

Figure B2: Flux and Energy Mass Absorption Coefficients in Ordinary Concrete as Functions of Photon Energy. Photon energy (MeV) is shown on the x-axis and absorption coefficient (cm^2/g) is shown on the y-axis. Both flux {μ/ρ (cm^2/g)} and energy {μ_{en}/ρ (cm^2/g)} mass attenuation coefficients are shown.

At photon energies of <1 10^{-2} MeV (10 keV), attenuation coefficients are so large that emissions from objects are very limited. Thus, this energy range can be neglected in the calculations. Thus, the remainder of this section addresses only photon emissions with energies of above 10 keV.

Having obtained the flux, it is necessary to multiply by a flux to effective dose rate conversion factor. This is obtained as the product of the flux to air kerma factor from Table A.1 of ICRP (1996) and the air kerma to effective dose rate factor for rotational geometry from Figure 8 of ICRP (1996). These factors together with the relevant flux and energy mass attenuation coefficients are listed in Table B7.

The results in Table B7 demonstrate that photon energies of below 20 keV do not have to be considered, i.e. most x-ray emissions are of limited relevance. However, in order to simplify the analysis, it is preferable to be able to use total photon emissions by radionuclide. As most photons of relevance will be in the range 0.1 to 2 MeV, examination of Table B7 shows that a cautious, but reasonable approach is to use an energy mass attenuation coefficient of 0.03 $cm^2\ g^{-1}$ in the derivation of H_v. Table B8 compares values of H_v derived for different values of μ_{en}/ρ and R using:

$$H_v = \{1.0 + 0.86/((x + R)/R)^{1.8}\}\{\exp(-[\mu_s R]^{0.4}\}$$

where x (m) is the distance from the surface of the sphere to the point at which the dose is evaluated. In these calculations, the density of ordinary concrete is taken as 2.35 g cm^{-3}.

Table B7: Attenuation and Flux Conversion Factors over the Photon Energy Range of Relevance

Energy (MeV)	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)	Flux to Air Kerma Conversion Factor (pGy cm^2)	Air Kerma to Effective Dose Conversion Factor (Sv/Gy)	Flux to Effective Dose Rate Factor (pSv cm^2)
1.0000E-02	2.0450E+01	1.9370E+01	7.43	0.00	0.00
1.5000E-02	6.3510E+00	5.8550E+00	3.12	0.00	0.00
2.0000E-02	2.8060E+00	2.4620E+00	1.68	0.03	0.05
3.0000E-02	9.6010E-01	7.1570E-01	0.72	0.15	0.11
4.0000E-02	5.0580E-01	2.9950E-01	0.43	0.45	0.19
5.0000E-02	3.4120E-01	1.5630E-01	0.32	0.70	0.23
6.0000E-02	2.6600E-01	9.5540E-02	0.29	0.90	0.26
8.0000E-02	2.0140E-01	5.0500E-02	0.31	0.98	0.30
1.0000E-01	1.7380E-01	3.6490E-02	0.37	0.97	0.36
1.5000E-01	1.4360E-01	2.8970E-02	0.60	0.90	0.54
2.0000E-01	1.2820E-01	2.8680E-02	0.86	0.87	0.74
3.0000E-01	1.0970E-01	2.9690E-02	1.38	0.82	1.13
4.0000E-01	9.7830E-02	3.0240E-02	1.89	0.82	1.55
5.0000E-01	8.9150E-02	3.0330E-02	2.38	0.81	1.93
6.0000E-01	8.2360E-02	3.0150E-02	2.84	0.82	2.33
8.0000E-01	7.2270E-02	2.9400E-02	3.69	0.82	3.03
1.0000E+00	6.4950E-02	2.8430E-02	4.47	0.83	3.71
1.5000E+00	5.2880E-02	2.5950E-02	6.14	0.86	5.28
2.0000E+00	4.5570E-02	2.3950E-02	7.55	0.90	6.80
3.0000E+00	3.7010E-02	2.1200E-02	9.96	0.91	9.06
4.0000E+00	3.2170E-02	1.9510E-02	12.10	0.92	11.13
5.0000E+00	2.9080E-02	1.8400E-02	14.10	0.93	13.11
6.0000E+00	2.6970E-02	1.7630E-02	16.10	0.94	15.13
8.0000E+00	2.4320E-02	1.6690E-02	20.10	0.95	19.10
1.0000E+01	2.2780E-02	1.6170E-02	24.00	0.95	22.80

Table B8: Computation of H_v

***x* = 0.1 m**	***μ* (cm^2 g^{-1})**									
***R* (m)**	**2.5**	**1**	**0.25**	**0.1**	**0.075**	**0.05**	**0.04**	**0.03**	**0.02**	**0.015**
0.1	7.60E-03	3.63E-02	1.64E-01	3.05E-01	3.56E-01	4.29E-01	4.70E-01	5.23E-01	5.95E-01	6.45E-01
0.2	1.69E-03	1.33E-02	9.71E-02	2.21E-01	2.70E-01	3.46E-01	3.90E-01	4.49E-01	5.33E-01	5.93E-01
0.4	2.19E-04	3.34E-03	4.59E-02	1.36E-01	1.77E-01	2.46E-01	2.88E-01	3.47E-01	4.35E-01	5.00E-01
0.6	4.81E-05	1.19E-03	2.58E-02	9.25E-02	1.27E-01	1.86E-01	2.24E-01	2.78E-01	3.63E-01	4.28E-01
0.8	1.38E-05	5.04E-04	1.60E-02	6.68E-02	9.50E-02	1.46E-01	1.80E-01	2.30E-01	3.10E-01	3.73E-01
1	4.71E-06	2.40E-04	1.05E-02	5.03E-02	7.38E-02	1.18E-01	1.49E-01	1.94E-01	2.69E-01	3.29E-01
1.5	5.05E-07	5.14E-05	4.38E-03	2.76E-02	4.34E-02	7.56E-02	9.89E-02	1.35E-01	1.99E-01	2.52E-01
2	8.14E-08	1.46E-05	2.14E-03	1.68E-02	2.80E-02	5.21E-02	7.05E-02	1.00E-01	1.54E-01	2.01E-01
***x* = 1 m**	***μ* (cm^2 g^{-1})**									
***R* (m)**	**2.5**	**1**	**0.25**	**0.1**	**0.075**	**0.05**	**0.04**	**0.03**	**0.02**	**0.015**
0.1	6.16E-03	2.95E-02	1.33E-01	2.48E-01	2.89E-01	3.48E-01	3.81E-01	4.24E-01	4.83E-01	5.23E-01
0.2	1.24E-03	9.74E-03	7.10E-02	1.61E-01	1.98E-01	2.53E-01	2.85E-01	3.28E-01	3.90E-01	4.33E-01
0.4	1.52E-04	2.31E-03	3.18E-02	9.40E-02	1.23E-01	1.70E-01	1.99E-01	2.40E-01	3.01E-01	3.46E-01
0.6	3.34E-05	8.24E-04	1.79E-02	6.43E-02	8.79E-02	1.29E-01	1.56E-01	1.93E-01	2.52E-01	2.98E-01
0.8	9.78E-06	3.56E-04	1.13E-02	4.73E-02	6.72E-02	1.03E-01	1.28E-01	1.63E-01	2.20E-01	2.64E-01
1	3.40E-06	1.73E-04	7.60E-03	3.63E-02	5.34E-02	8.56E-02	1.08E-01	1.40E-01	1.95E-01	2.38E-01
1.5	3.84E-07	3.91E-05	3.33E-03	2.10E-02	3.30E-02	5.75E-02	7.52E-02	1.03E-01	1.51E-01	1.92E-01
2	6.44E-08	1.15E-05	1.69E-03	1.33E-02	2.21E-02	4.12E-02	5.58E-02	7.92E-02	1.22E-01	1.59E-01
***x* = 10 m**	***μ* (cm^2 g^{-1})**									
***R* (m)**	**2.5**	**1**	**0.25**	**0.1**	**0.075**	**0.05**	**0.04**	**0.03**	**0.02**	**0.015**
0.1	6.10E-03	2.92E-02	1.31E-01	2.45E-01	2.85E-01	3.44E-01	3.77E-01	4.19E-01	4.78E-01	5.17E-01

0.2	1.20E-03	9.43E-03	6.87E-02	1.56E-01	1.91E-01	2.45E-01	2.76E-01	3.18E-01	3.77E-01	4.19E-01
0.4	1.39E-04	2.13E-03	2.92E-02	8.65E-02	1.13E-01	1.57E-01	1.83E-01	2.21E-01	2.77E-01	3.18E-01
0.6	2.93E-05	7.21E-04	1.57E-02	5.63E-02	7.70E-02	1.13E-01	1.36E-01	1.69E-01	2.21E-01	2.61E-01
0.8	8.21E-06	2.99E-04	9.50E-03	3.97E-02	5.65E-02	8.69E-02	1.07E-01	1.37E-01	1.84E-01	2.22E-01
1	2.76E-06	1.41E-04	6.16E-03	2.95E-02	4.33E-02	6.94E-02	8.72E-02	1.14E-01	1.58E-01	1.93E-01
1.5	2.92E-07	2.98E-05	2.54E-03	1.60E-02	2.51E-02	4.37E-02	5.73E-02	7.83E-02	1.15E-01	1.46E-01
2	4.71E-08	8.43E-06	1.24E-03	9.74E-03	1.62E-02	3.01E-02	4.08E-02	5.79E-02	8.92E-02	1.16E-01

As expected, there is only a weak dependence on x, because this is taken into account by defining $H_v = G_v(a/R)^2$. There is a strong dependence on R for large values of μ. However, for a value of μ of 0.1 $cm^2\ g^{-1}$, the variation is about a factor of 20 between spheres of radius 0.1 m and those of radius 2 m. This value of μ corresponds to a photon energy of about 60 keV. For higher-energy photons, a value of of μ of 0.03 $cm^2\ g^{-1}$ is typical and the range of variation is about a factor of five.

In view of these results, a value of μ of 0.03 $cm^2\ g^{-1}$ is adopted in the dose calculations presented here. This converts to 0.07 cm^{-1} for ordinary concrete. This is realistic for photons in the energy range 0.1 to 2.0 MeV and is cautious for softer photons. Thus, the resultant scale factors $F = R(R/a)^2 H_v(a/R, \mu_s R, 0)/\pi$ are as listed in Table B9.

Table B9: Estimation of Scale Factors for Volume Sources

$(R/a)^2$	0.1	0.2	0.4	0.6	0.8	1	1.5	2
0.3	6.25E-02	1.60E-01	3.27E-01	4.44E-01	5.29E-01	5.92E-01	6.94E-01	7.56E-01
1.0	8.26E-03	2.78E-02	8.16E-02	1.41E-01	1.98E-01	2.50E-01	3.60E-01	4.44E-01
3.0	1.04E-03	3.91E-03	1.38E-02	2.78E-02	4.43E-02	6.25E-02	1.11E-01	1.60E-01
a/R	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	4.00	2.50	1.75	1.50	1.38	1.30	1.20	1.15
1.0	11.00	6.00	3.50	2.67	2.25	2.00	1.67	1.50
3.0	31.00	16.00	8.50	6.00	4.75	4.00	3.00	2.50
H_v	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	0.45	0.37	0.29	0.24	0.20	0.17	0.13	0.09
1.0	0.43	0.33	0.24	0.19	0.16	0.14	0.10	0.08
3.0	0.42	0.32	0.23	0.18	0.14	0.12	0.09	0.07
Scale Factor	**0.1**	**0.2**	**0.4**	**0.6**	**0.8**	**1**	**1.5**	**2**
0.3	8.95E-03	1.89E-02	3.02E-02	3.39E-02	3.41E-02	3.28E-02	2.76E-02	2.27E-02
1.0	1.12E-03	2.91E-03	6.26E-03	8.70E-03	1.03E-02	1.12E-02	1.19E-02	1.13E-02
3.0	1.39E-04	3.98E-04	9.91E-04	1.55E-03	2.02E-03	2.41E-03	3.06E-03	3.35E-03

Appendix B References

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Appendix C: Dose Factors for Small Sealed Sources

This Appendix sets out the theoretical basis for calculations of dose rates close to, or in contact with, small sources

It is useful to address both photon and beta doses close to small sources (treated as self-absorbing spheres surrounded by an absorbing medium). In order to keep the analysis simple, The results may be reported in terms of dose rate at an effective distance $r = \mu x$, where μ is the linear energy attenuation coefficient. This is a familiar concept for photons, but following Leichner (1994), a similar, effective quantity is introduced for beta particles. Note that though the analysis is mainly more general, where specific assumptions have to be made, a soft tissue equivalent medium is assumed.

For photons, Leichner (1994) expresses[16] the absorbed dose rate, D, from one type of photon emission from a radionuclide as:

$$D = CYE\varphi$$

where C (Bq kg^{-1}) is the activity concentration in the source;

Y (-) is the yield of the photon per transformation;

E (MeV) is the energy of the photon;

φ (-) is the point isotropic absorbed fraction.

Here, D has units of MeV s^{-1} kg^{-1}. However, it is necessary for D to have units of Sv h^{-1} or J h^{-1} kg^{-1}. Therefore, conversion factors of 1 MeV = 1.602 10^{-13} J and 1 hour = 3600 s are introduced. Thus:

$$D = 1.602\ 10^{-13} \times 3600\ CYE\varphi = 5.767\ 10^{-10}\ CYE\varphi \quad \text{Sv h}^{-1}$$

where the units are as specified above.

Leichner (1994) estimates φ outside a uniformly contaminated sphere:

$\varphi = \mu_{en}\sum\varphi_i$ where the summation is for i = 0,3 and μ_{en} (m^{-1}) is the linear energy photon absorption coefficient.

The four functions $\varphi_i(r)$ are given by:

$$\varphi_0 = (1/4\mu^2 b)\{[1-\mu(b-a)]\exp[-\mu(b+a)]-[1-\mu(b+a)]\exp[-\mu(b-a)]\} + [(a^2-b^2)/4b]\{E_1[\mu(b-a)] - E_1[\mu(b+a)]\}$$

$$\varphi_1 = (c_1/2bc^3\mu^2)\{(1+c\mu a)\exp[-c\mu(a+b)]- (1-c\mu a)\exp[-c\mu(b-a)]\}$$

$$\varphi_2 = (c_2/2bc^4\mu^2)\{[c^2\mu^2 a(a+b)+c\mu(3a+b)+3]\exp[-c\mu(a+b)]- [c^2\mu^2 a(a-b)+c\mu(b-3a)+3]\exp[-c\mu(b-a)]$$

[16] Different symbols from Leichner (1994), have been adopted but the form of the expressions is identical.

$$\varphi_3 = (c_3/2bc^5\mu^2)\{[c^3\mu^3a(a+b)^2+c^2\mu^2(5a^2+b^2+6ab)+6c\mu(2a+b)+12]\exp[-c\mu(a+b)]-$$

$$[-c^3\mu^3a(b-a)^2+c^2\mu^2(5a^2+b^2-6ab)+6c\mu(b-2a)+12]\exp[-c\mu(b-a)]$$

Note that a minor error in the printed version of Leichner (1994) has been corrected in the equation for φ_3. There the expression $\exp[-c\mu(a+b)]$ is given as $\exp[-c\mu(a-b)]$. This is clearly in error on the grounds of symmetry (see the expressions for φ_1 and φ_2) and also gives incorrect (non-convergent) results.

In the expression for φ_0, the function E_1 is the exponential integral. For real, non-zero values of its argument, $E_1(x)$ is defined by:

$E_1(x) = \int dt \exp(t)/t$ where the limits of the integration are $-\infty$ and x.

The value of E_1 can be obtained using a Taylor series expansion and extracting the logarithmic singularity. This yields:

$E_1(x) = \gamma + \ln(x) + \sum x^k/(k\times k!)$ where the summation is from k = 1, ∞ and γ is the Euler-Mascheroni constant. This is approximately 0.5772157.

Unfortunately, this series is extremely slow to converge. However, it is also known that $E_1(x)$ can be bracketed by elementary functions:

$E_1(x) > 0.5\exp(-x)\ln(1+2/x)$

$E_1(x) < \exp(-x)\ln(1+1/x)$

This bracketing approach is reasonably accurate at all x, as is illustrated in Figure C1. Therefore, for this analysis, an arithmetic mean of the two bracketing values has been used, i.e.

$E_1(x) \sim [0.5\exp(-x)\ln(1+2/x) + \exp(-x)\ln(1+1/x)]/2$

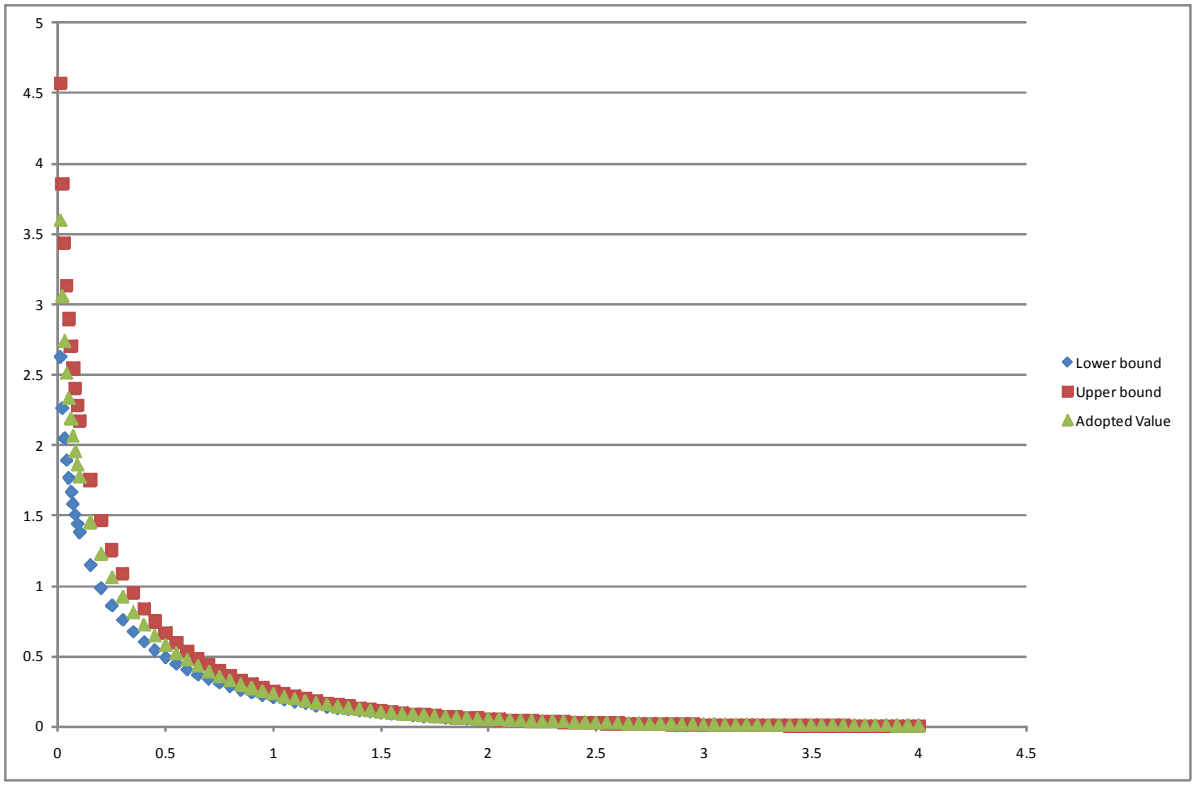

Figure C1: Approximation to the Exponential Integral E_1

The formulae for φ_i are characterised by the radius of the source sphere (a) and the distance from the centre of the sphere to the evaluation point (b). The coefficient c is defined by:

$c = 1 + c_4$

The coefficients, c_1 to c_4 are empirical fitting coefficients. The values given by Leichner (1994) are listed in Table C1.

Table C1: Empirical Coefficients for Photons

Energy (MeV)	c_1	c_2	c_3	c_4
0.015	0.247	-0.0298	0.00321	0.146
0.02	0.552	-0.0515	0.00631	0.135
0.03	1.32	0.00100	0.00297	0.0496
0.04	2.48	0.114	0.00142	0.000685
0.05	2.83	0.632	0.00862	0.000888
0.06	2.68	1.12	0.0365	0.000701
0.08	2.40	1.21	0.152	0.000728
0.10	2.28	0.979	0.215	0.000732
0.15	1.72	0.763	0.184	0.000782
0.20	1.58	0.602	0.128	0.00200
0.30	1.22	0.564	0.0539	0.00120
0.40	1.16	0.502	0.0208	0.00559
0.50	1.07	0.409	0.00964	0.00561
0.60	1.10	0.328	0.0131	0.0201
0.80	1.05	0.254	0.0140	0.0429
1.00	0.980	0.193	0.0152	0.0580
1.50	0.921	0.122	0.00775	0.0613
2.00	0.809	0.0786	0.00749	0.0716
3.00	0.745	0.0371	0.00596	0.0785

It is relevant to note that φ_i have dimensions of [L]. Thus, φ is dimensionless as required. This means that consistent calculations can be based on any length unit. Here metres are adopted, so a and b are given in metres and μ and μ_{en} are given in units of m^{-1}.

A simple spreadsheet has been developed to calculate values of φ. This is shown in Figure C2. In this figure cells containing the fitting parameters are shaded grey, input data to be varied by the user are shaded yellow, intermediate calculations are shaded blue, and results are shaded orange.

Energy (MeV)	c_1	c_2	c_3	c_4	c	Phi0	Phi1	Phi2	Phi3	Phi
0.015	0.247	-0.0298	0.00321	0.146	1.146	-4.17E-13	7.81E-14	-2.2433E-13	5.76E-13	6.38E-15
0.02	0.552	-0.0515	0.00631	0.135	1.135	-4.17E-13	2.27E-13	-5.0398E-13	1.47E-12	3.89E-13
0.03	1.32	0.001	0.00297	0.0496	1.0496	-4.17E-13	4.16E-12	7.52485E-14	5.35E-12	4.58E-12
0.04	2.48	0.114	0.00142	0.000685	1.000685	-4.17E-13	2.52E-11	2.76655E-11	8.26E-12	3.03E-11
0.05	2.83	0.632	0.00862	0.000888	1.000888	-4.17E-13	2.86E-11	1.52629E-10	4.99E-11	1.15E-10
0.06	2.68	1.12	0.0365	0.000701	1.000701	-4.17E-13	2.72E-11	2.71697E-10	2.12E-10	2.55E-10
0.08	2.4	1.21	0.152	0.000728	1.000728	-4.17E-13	2.43E-11	2.9334E-10	8.83E-10	6.00E-10
0.1	2.28	0.979	0.215	0.000732	1.000732	-4.17E-13	2.31E-11	2.37316E-10	1.25E-09	7.54E-10
0.15	1.72	0.763	0.184	0.000782	1.000782	-4.17E-13	1.74E-11	1.84735E-10	1.07E-09	6.35E-10
0.2	1.58	0.602	0.128	0.002	1.002	-4.17E-13	1.55E-11	1.41562E-10	7.21E-10	4.39E-10
0.3	1.22	0.564	0.0539	0.0012	1.0012	-4.17E-13	1.22E-11	1.35193E-10	3.1E-10	2.28E-10
0.4	1.16	0.502	0.0208	0.00559	1.00559	-4.17E-13	1.05E-11	1.08319E-10	1.08E-10	1.13E-10
0.5	1.07	0.409	0.00964	0.00561	1.00561	-4.17E-13	9.65E-12	8.82097E-11	4.98E-11	7.36E-11
0.6	1.1	0.328	0.0131	0.0201	1.0201	-4.17E-13	7.01E-12	4.99991E-11	4.78E-11	5.22E-11
0.8	1.05	0.254	0.014	0.0429	1.0429	-4.17E-13	3.88E-12	2.24356E-11	2.96E-11	2.77E-11
1	0.98	0.193	0.0152	0.058	1.058	-4.17E-13	2.53E-12	1.18798E-11	2.24E-11	1.82E-11
1.5	0.921	0.122	0.00775	0.0613	1.0613	-4.17E-13	2.19E-12	6.93975E-12	1.05E-11	9.63E-12
2	0.809	0.0786	0.00749	0.0716	1.0716	-4.17E-13	1.51E-12	3.49519E-12	7.96E-12	6.27E-12
3	0.745	0.0371	0.00596	0.0785	1.0785	-4.17E-13	1.18E-12	1.39896E-12	5.37E-12	3.76E-12

a	5
b	50
μ	0.5
μ_{en}	0.5
b-a	45
b+a	55
μ(b-a)	22.5
μ(b+a)	27.5
f1	0.02
f2	4.45902E-09
f3	-12.375
E1 n	7.28058E-12
E1 m	4.03672E-14
f4	-8.9598E-11
f5	8.91804E-11
f6	-4.172E-13

Figure C2: Spreadsheet for Absorbed Fraction Calculations

Leichner (1994) has identified that a similar approach can be adopted for beta particles. The equations given above for photons can be used with the following substitutions:

$\mu \rightarrow \mu^*$

$\mu_{en} \rightarrow G_0$

$c_1 \rightarrow d_1$

$c_2 \rightarrow d_2$

$c_3 \rightarrow d_3$

$c \rightarrow d_4$

For a tissue equivalent medium:

$\mu^* = 0.474E^{-2} + 5.80E^{-0.82}$

where μ^* has units of $cm^2\ g^{-1}$ and E (MeV) is the average energy of the emitted beta particles. As soft tissue has a density of approximately 1 g cm^{-3}, the numerical value of μ^* calculated in this way can be interpreted as a linear attenuation coefficient with units of cm^{-1}.

G_0 is a normalisation coefficient. It is estimated here by calibration, as discussed below.

Leichner (1994) gives values of d_1 to d_4 for various radionuclides. In Table E2, these are listed together with the mean beta energies per transformation and the corresponding value of μ^*. These values of μ^* have been calculated explicitly and differ slightly from those listed by Leichner (1994).

Table C2: Coefficients for Beta Emitters

Radionuclide	Mean beta energy (MeV)	d_1	d_2	d_3	d_4	μ^* ($cm^2\ g^{-1}$)
H-3	5.683E-3	0.581	-0.258	0.240	1.36	1.51E+04
C-14	4.945E-2	-0.585	0.722	0.0	1.36	2.62E+02
S-35	4.88E-2	-1.03	0.734	0.0	1.43	2.68E+02
I-131	0.190	-1.12	1.09	0.0	1.44	3.58E+01
Ag-111	0.354	-0.564	1.38	0.0	1.45	1.74E+01
P-32	0.6947	1.00	0.350	1.49	1.66	8.80E+00
Y-90	0.935	0.684	0.114	1.38	1.59	6.67E+00
Rh-106	1.41	1.01	0.490	1.40	1.61	4.61E+00

The various coefficients show no particular trend with mean beta energy (see Figure E3), so linear interpolation is considered appropriate for estimating values at intermediate energies.

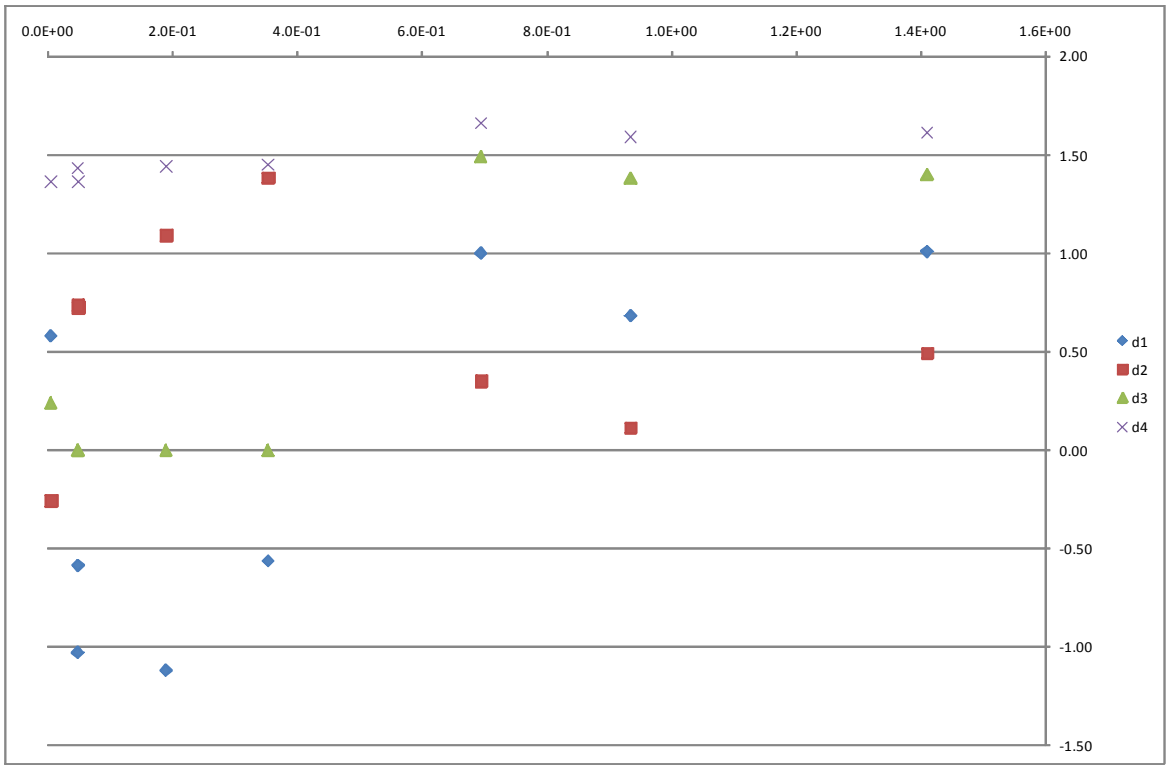

Figure C3: Coefficients for Use in Beta Dose Calculations (Mean Energy in MeV is plotted on the x axis)

A simple spreadsheet for estimating values of φ is shown in Figure C4. Note that the lower part of the spreadsheet is simply concerned with performing a linear interpolation in energy.

Energy (MeV)	d_1	d_2	d_3	d_4	c	Phi0	Phi1	Phi2	Phi3	Phi
0.185	-1.10E+00	1.08E+00	0.00E+00	1.44E+00	1.44E+00	0.19	-0.16	0.25	0.00	0.14
a	5									
b	6									
μ*	0.5									
G_0	0.5									
b-a	1									
b+a	11									
μ(b-a)	0.5									
μ(b+a)	5.5									
f1	0.166666667									
f2	2.731431354									
f3	-0.45833333									
E1 n	0.577214378									
E1 m	0.000658239									
f4	-0.2642549									
f5	0.455238559									
f6	0.190983662									

Mean beta energy (MeV)	d_1	d_2	d_3	d_4
0	0.581	-0.258	0.24	1.36
5.68E-03	0.581	-0.258	0.24	1.36
4.88E-02	-1.03	0.734	0	1.43
4.95E-02	-0.585	0.722	0	1.36
0.19	-1.12	1.09	0	1.44
0.354	-0.564	1.38	0	1.45
0.6947	1	0.35	1.49	1.66
0.935	0.684	0.114	1.38	1.59
1.41	1.01	0.49	1.4	1.61
10	1.01	0.49	1.4	1.61

Beta energy (MeV)												
0.185	0.5	0.5	0.5	0.5	2.50E-01	2.50E-01	2.50E-01	2.50E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.5	0.5	0.5	0.5	2.50E-01	2.50E-01	2.50E-01	2.50E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.5	0.5	0.5	0.5	2.50E-01	2.50E-01	2.50E-01	2.50E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	0.5	0.5	0.5	0.5	1.00E+00	1.00E+00	1.00E+00	1.00E+00	-1.10E+00	1.08E+00	0.00E+00	1.44E+00
	2	2	2	2	4.00E+00	4.00E+00	4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2	2	2	2	4.00E+00	4.00E+00	4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2	2	2	2	4.00E+00	4.00E+00	4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2	2	2	2	4.00E+00	4.00E+00	4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2	2	2	2	4.00E+00	4.00E+00	4.00E+00	4.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	2	2	2	2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	-1.10E+00	1.08E+00	0.00E+00	1.44E+00

Figure C4: Spreadsheet for Beta Calculation

For spheres large compared with the beta range, the dose rate at the surface would be expected to be half that within an infinite medium. The dose rate in an infinite medium is given by:

$D_\infty = 1.602\ 10^{-13} \times 3600\ CYE$

The beta dose rate is given by:

$D = 1.602\ 10^{-13} \times 3600\ CYE\varphi$

Therefore, the value of φ should be 0.5 at the surface of large self absorbing spheres. Here, the assumption is made as a first approximation that $G_0 = \mu^*$. This has been tested for 10 cm radius spheres, calculating φ at a radial distance of 0.0001 cm greater than the radius of the sphere, for the various beta energies and μ^* values listed in Table 3. The very low energy beta emitters were excluded from this calculation, because of their high degree of absorption. For C-14 and S-35, spheres of radius 1 cm were used, with the calculation made at 1.0001 cm. For H-3, the calculation was made for a sphere of radius 0.01 cm, with the dose point at 0.010001 cm. The value of φ obtained were 0.58, 0.81, 1.33, 1.29 and 1.41 at energies of 0.19 to 1.41 MeV and 0.58, 0.45 and 0.73 for the very low energy beta emitters. The mean of the higher energy values is 1.08 and of the lower energy values is 0.59. The overall mean is 0.90. This suggests that the assumption that $G_0 = 0.5\mu^*$, will be accurate to within about a factor of two for beta particles of any energy.

Finally, it should be noted that all the calculations given above are appropriate to material with the same degree of sorption both inside the source sphere and outside it. The calculation for a sphere located in a low sorption medium such as air can be estimated as follows. Let the radius of the sphere be a and the dose point be located at b. Let the absorption coefficient within the sphere be μ (or μ^*). Calculate the value dose rate D just outside the surface of the sphere, i.e. at $a+\Delta$. For distances $b > 2a$, it is reasonable to approximate the sphere as a point source, so the dose rate can be scaled as $Db^2/(a+\Delta)^2$.

Consider an illustrative application to a Sr-90/Y-90 source of density identical to soft tissue (1000 kg/m^3) and radius 0.01 m. Sr-90 emits a beta particle with a mean energy of 0.196 MeV. Consider Y-90 to be present in secular equilibrium. It emits a beta particle with a mean energy of 0.935 MeV. The values of φ just outside the sphere are 0.29 for Sr-90 and 0.57 for Y-90.

The mass of the sphere is 0.00419 kg For a 1 MBq source, the concentration is 2.39 10^8 Bq/kg. Thus, dose rates just outside the sphere are:

$1.602\ 10^{-13} \times 3600 \times 2.39\ 10^8 \times 0.196 \times 0.29 = 7.83\ 10^{-3}$ Sv/h for Sr-90

$1.602\ 10^{-13} \times 3600 \times 2.39\ 10^8 \times 0.935 \times 0.57 = 7.35\ 10^{-2}$ Sv/h for Y-90

Neglecting absorption in air, at 10 cm from the centre of the sphere, the dose rates will be a factor of 100 lower.

For comparison, for an un-attenuated source of 1 MBq, the flux at 10 cm is 796 particles cm^{-2} s^{-1}. Figure 34 of ICRP (1996) gives a conversion coefficient for directional dose equivalent at a depth of 0.07 mm of around 0.2 nSv cm^2 for an electron energy of about 1 MeV. Therefore, the dose rate from Y-90 at 10 cm is estimated as $796 \times 3600 \times 2\ 10^{-9} = 5.73\ 10^{-3}$ Sv/h. From the detailed calculation above, the dose rate is estimated to be $7.35\ 10^{-4}$ Sv/h. This is lower by a factor of 8 because of self absorption in the sphere (μ^*r is 6.6 in this case).

Appendix C References

ICRP, 1996. Conversion Coefficients for use in Radiological Protection against External Radiation, ICRP Publication 74, Annals of the ICRP, **26(3/4)**.

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Appendix D: Dose Factors around Point Sources

ICRP publication 107 (ICRP, 2008) provides air kerma values for photons, as described in the main text. This Appendix describes the additional calculations that are required to define contributions from electron emissions including beta particles, Auger electrons and internal conversion electrons.

In Appendix C, it is explained how the absorbed dose rate in tissue equivalent material surrounding a sphere of uniformly contaminated tissue equivalent material is calculated

As the interest is in small sources values of φ for a source of radius 0.01 cm. The value of φ is here calculated just outside that source, i.e. at 0.010001 cm from its centre (or 1 µm beyond its boundary). Values of mean beta energy (E) and μ^* used in that calculation were as listed in Table D1. Throughout $G_0 = 0.5\ \mu^*$.

Table D1: Computed Values of φ

Mean beta energy (MeV)	μ^* ($cm^2\ g^{-1}$)	φ
5.683E-3	1.51E+04	0.2746
4.945E-2	2.62E+02	0.2258
0.190	3.58E+01	0.0609
0.354	1.74E+01	0.0373
0.6947	8.80E+00	0.0218
0.935	6.67E+00	0.0163
1.41	4.61E+00	0.0115

As a check, φ may be recomputed for a source of radius 0.02 cm, again at 1 µm beyond its boundary. As the source strength is increased by a factor of eight, but the scale factor to unit distance (see below) is decreased by a factor of 4, it was predicted that the value of φ would increase by a factor of two for energetic beta particles and rather less than this for low energy betas, since self-absorption (even in a very small source) is significant at low beta energies. The new φ values obtained showed an increase of a factor of 1.27 at at 0.04945 MeV and a factor of 2 at 1.41 MeV This provides added confidence in the approach adopted.

The calculations are for a 1 Bq source. As the calculation uses the concentration C, it is appropriate to note that:

$$C = 1/\{(4\pi/3)a^3\rho\}$$

where a is the radius of the source (0.01 cm) and ρ (kg cm^{-3}) is its density. The density of soft tissue is taken as 0.001 kg cm^{-3}. Thus, C = 2.39 10^8 Bq kg^{-1}. Furthermore, the dose rate, D (Gy s^{-1}) is given at 0.01 cm and it is required at unit distance (1 m = 100 cm) in vacuum. Therefore, a factor of 1 10^{-8}, i.e. $(0.01/100)^2$ is introduced by inverse square law considerations. Thus:

$$D^* = 1.602\ 10^{-13} \times 2.39\ 10^8 \times 1\ 10^{-8} YE\varphi \qquad \text{Gy m}^2 \text{ per Bq s}$$

or

$D^* = 3.829\ 10^{-13} YE\varphi$ Gy m^2 per Bq s

These values have been interpolated to give the overall results shown in Table D2 (note that these values include contributions from Auger and Internal Conversion electrons).

Results of the calculations are shown in Table D2.

Table D2: Photon and Beta Dose Factors (*Gy m^2 per Bq s from ICRP Publication 107, **Gy m^2 per Bq s computed as described here)

Chain	Chain Member	Branching Ratio	Dose Factor*	Photon Dose Factor for Chain	Mean Beta Energy (MeV per transformation)	Phi Value	Beta Dose Factor**	Beta Dose Factor for Chain
Co-60	Co-60	1	8.53E-17	***8.53E-17***	0.0969	0.170	6.31E-15	***6.31E-15***
Sr-90	Sr-90	1	0.00E+00	***1.65E-21***	0.1957	0.060	4.50E-15	***1.03E-14***
	Y-90	1	1.65E-21		0.9331	0.016	5.83E-15	
Cs-137	Cs-137	1	6.11E-23	***2.13E-17***	0.1884	0.063	4.53E-15	***6.39E-15***
	Ba-137m	0.944	2.26E-17		0.0653	0.0788	1.97E-15	
Ra-226	Ra-226	1	5.23E-19	***6.52E-17***	0.0039	0.2770	4.14E-16	***1.15E-14***
	Rn-222	1	1.50E-20		0	0.0000	0.00E+00	
	Po-218	1	0.00E+00		0	0.0000	0.00E+00	
	Pb-214	1	1.48E-17		0.2948	0.0458	5.17E-15	
	Bi-214	1	4.99E-17		0.6631	0.0232	5.89E-15	
	Po-214	1	3.07E-21		0	0.0000	0.00E+00	
Pb-210	Pb-210	1	9.72E-18	***9.72E-18***	0.0404	0.2360	3.65E-15	***8.97E-15***
	Bi-210	1	1.53E-23		0.3889	0.0357	5.32E-15	
	Po-210	1	3.60E-22		0	0.0000	0.00E+00	
Th-232	Th-232	1	2.26E-18	***2.26E-18***	0.0126	0.2670	1.29E-15	***1.29E-15***
Ra-228	Ra-228	1	3.85E-18	***4.38E-17***	0.0132	0.2660	1.34E-15	***7.02E-15***
	Ac-228	1	3.99E-17		0.4494	0.0330	5.68E-15	
Th-228	Th-228	1	2.82E-18	***5.79E-17***	0.021	0.2580	2.08E-15	***1.55E-14***
	Ra-224	1	4.96E-19		0.0023	0.2780	2.45E-16	
	Rn-220	1	2.41E-20		0	0.0000	0.00E+00	
	Po-216	1	5.66E-22		0	0.0000	0.00E+00	
	Pb-212	1	1.09E-17		0.1766	0.0766	5.18E-15	

Chain	Chain Member	Branching Ratio	Dose Factor*	Photon Dose Factor for Chain	Mean Beta Energy (MeV per transformation)	Phi Value	Beta Dose Factor**	Beta Dose Factor for Chain
	Bi-212	1	7.05E-18		0.5046	0.0304	5.88E-15	
	Po-212	0.6407	0.00E+00		0	0.0000	0.00E+00	
	Tl-208	0.3593	1.02E-16		0.6113	0.0256	5.99E-15	
Am-241	Am-241	1	9.80E-18	***9.80E-18***	0.0373	0.2390	3.41E-15	***3.41E-15***
H-3	H-3	1	0	***0.00E+00***	0.0057	0.2750	6.004E-16	***6.00E-16***
C-14	C-14	1	0	***0.00E+00***	0.0494	0.2260	4.276E-15	***4.28E-15***
Cl-36	Cl-36	1	5.38E-21	***5.38E-21***	0.2732	0.0489	5.117E-15	***5.12E-15***
Ni-63	Ni-63	1	0	***0.00E+00***	0.0174	0.2620	1.746E-15	***1.75E-15***
Np-237	Np-237	1	1.55E-17	***3.60E-17***	0.0681	0.2040	5.321E-15	***1.00E-14***
	Pa-233	1	2.05E-17		0.215	0.0573	4.718E-15	
Pu-239	Pu-239	1	1.11E-18	***1.11E-18***	0.0074	0.2730	7.737E-16	***7.74E-16***

Note that all radionuclides are all treated as single-member chains, except for Np-237, which is taken to be present with Pa-233 in secular equilibrium. As the branching ratio to Pa-233 is 1.0, the activity of Pa-233 is equal to the activity of Np-237.

Factors are given by chain member. Also, the sum over the chain of the product of branching ratio and dose factor is given. The photon factors are taken directly from ICRP Publication 107. The beta factors are computed as described above. In most cases the beta yield per transformation is 1.0, so the mean beta energy is equal to the mean energy per transformation. However, for Po-218 and Bi-212 this is not the case. These have yields of 2 10^{-4} and 0.6406 of beta particles with mean energies of 0.07137 and 0.7694 MeV, respectively. This has been taken into account in the derivation of values of φ.

It should be noted that these dose factors apply at 1 m from point sources in vacuum. Values at other distances in vacuum can be calculated by application of the inverse square law. For distances of up to a few metres, the attenuation of the photon fluxes in air will not be significant. However, the beta fluxes will be substantially attenuated by absorption in air and clothing. Also, the dose rates are for a small volume of tissue equivalent material and absorption in tissues overlying sensitive cells (typically taken at a depth of 70 µm in skin) is neglected.

Finally, consideration needs to be given to the application of these factors. It is envisaged that the main significance will be in determining dose rates to the skin. For protection of the skin, ICRP Publication 103 (IRCP, 2007), Table 6, recommends limits on equivalent dose of 500 mSv for occupational exposure and 50 mSv for public exposure. These limits relate to the prevention of deterministic effects. The dose is to be calculated averaged over 1 cm^2 of skin regardless of the area exposed. In the context of the above, provided that the point source is more than a few centimetres from the skin, the point estimates given above will also closely approximate to the averages applicable over 1 cm^2 or more.

Appendix D References

ICRP, 2008. ICRP Publication 107: Nuclear Decay Data for Dosimetric Calculations. Annals of the ICRP, **38(3)**, International Commission on Radiological Protection.

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection, Annals of the ICRP **37(2-4)**, International Commission on Radiological Protection.