

4.1.2 Electron Data

The electron source term data are comprised of emitted atomic electrons, internal conversion and Auger-electrons, and beta (β) radiations termed continuous radiation due to the associated continuous energy spectra. As with the alpha data, the mass of each member of the parent/progeny series decay chain is determined at a 15 year post purification date. The information provided in this section is based on work by Becker (1994).^k

The total atomic electron source term per parent in units of keV/sec is computed using the total average electron energy per disintegration, $\langle e \rangle$, (keV/dis) as tabulated in the Table of Radioactive Isotopes.⁴² The value $\langle e \rangle$ is multiplied by the respective parent/progeny radionuclide decay rate, disintegrations/second, as computed at 15 years from time zero due to an initial parent/parent compound mass of one gram. This same process is followed for the continuous β radiation source by multiplying the total average β energy per disintegration $\langle \beta \rangle$, (keV/dis), by the respective parent/progeny radionuclide activity, (dis/sec), at the 15 year decay time.

For those individual chain members yielding atomic electrons, internal conversion/Auger-electrons, and continuous β radiations, the total average energy per disintegration is the sum of the components. This value is then multiplied by the disintegration rate of a given radionuclide to arrive at the electron energy emission rate in keV/sec. The total average electron energy emission rate for a given parent/progeny chain is obtained by summing the computed energy emission rate contributed by each member of the chain at 15 years. The radon exception noted for the alpha source term computations also applies to the electron source term.

The results of the electron source term evaluation for the list of radionuclides identified in Table 4-5 is shown in Table 4-20. The californium isotope, although listed in Table 4-5, is omitted as there are no tabulated Evaluated Nuclear Structure Data File (ENSDF) data regarding electron decay modes and the intensities of the ²⁵²Cf fission products. This is of no great significance as there are only one or two drums listed in the Transuranic Waste Database (TWDB) which indicate the presence of californium. Additionally, the contribution to the electron source term from the progeny of these californium spontaneous fission decays can safely be dismissed due to the very low branching ratios.

No adjustment has been made for subsequent electron radiation interactions with either the source material itself or the waste matrix. The tabulated data is strictly the total energy emission rate per second computed as described.

4.1.3 Photon Data

The photon source term includes all γ -rays and x-rays associated with the parent/progeny decay chain members. The information provided in this section is based on work by Becker (1994).^k

k. G. K. Becker, *Low-Level Alpha Contaminated and Transuranic Waste Photon/Electron Source Term Data*, RWMC EDF-669, January 10, 1994.

Table 4-20. Total electron yield per gram parent material at 15 years post purification.^a

<u>Radionuclide source material</u>	<u>Total electron energy (keV/sec)</u>
²⁴¹ Am	3.7643E+12
²⁴³ Am	1.3057E+12
²⁵² Cf	—
²³⁷ Np	1.6687E+09
²³⁶ Pu	7.1147E+14
²³⁸ Pu	5.5795E+12
²³⁹ Pu	7.5145E+03
²⁴⁰ Pu	4.0903E+04
²⁴¹ Pu	1.1589E+13
²⁴² Pu	1.1762E+09
²²⁶ Ra	3.6877E+13
²³⁰ Th	5.1243E+09
²³² Th	3.7349E+05
²³³ U	2.0408E+09
²³⁵ U	1.7434E+07
²³⁸ U	6.3847E+06
HS Pu	4.7059E+12
WG Pu	4.0825E+10

a. EDF RWMC-669, 1/10/94.

The data source utilized in the determination of the photon source term is the Table of Radioactive Isotopes published in 1986.⁴⁻² The data for this publication came from the ENSDF, from which the Nuclear Data Sheets are published as they existed circa 1984. Some of the ENSDF data has been edited by the authors prior to its inclusion in the Table of Radioactive Isotopes in addition to local INEL-based edits resulting from specialized evaluations. Therefore, the data file utilized in the source term calculations is a modified version of the original ENSDF data.

In order to interpret the photon source term data, it is necessary to delineate the manner in which it was derived to establish a baseline for its subsequent use. As with the alpha and electron source terms, all photon source term data is based on an initial one-gram mass of a given parent radionuclide or parent radionuclidic compound such as weapons-grade plutonium (WG Pu). The parent radionuclides and radionuclidic compounds considered in this evaluation are again as specified in Table 4-5, and the nominal radionuclidic composition of the two compounds, WG Pu and HS Pu, are shown in Table 4-6.

The photon source term is computed for each indicated parent radionuclide and/or compound at 15 years post purification. As with the alpha and electron source terms, this requires that the decay and ingrowth of all members of the parent/progeny decay chain be accounted for at 15 years from time zero, where time = 0 is the time when the parent radionuclide or radionuclide compound mass is one gram. Thus all computations yield the photon emission rate (photons/second-energy group) due to an initial one gram time zero mass of parent material at a 15-year decay/ingrowth date. The photons are grouped into 50 keV-wide energy bins to simplify downstream computations.

To illustrate, the radionuclide chain members which are components of the photon source specified at 15 years post purification for ^{236}Pu are: $^{236}\text{Pu} \rightarrow ^{232}\text{U} \rightarrow ^{228}\text{Th} \rightarrow ^{224}\text{Ra} \rightarrow ^{220}\text{Rn} \rightarrow ^{216}\text{Po} \rightarrow ^{212}\text{Pb} \rightarrow \dots$ $^{212}\text{Bi} \rightarrow (\alpha = 0.3594) ^{208}\text{Tl} \rightarrow ^{208}\text{Pb}$:: $^{212}\text{Bi} \rightarrow (\beta = 0.6406) ^{212}\text{Po} \rightarrow ^{208}\text{Pb}$. The mass of each radionuclide in the chain is determined at 15 years and the photon yield associated with that mass is summed together to obtain the total photon source term for the parent/progeny source at 15 years.

The exception to this method involves the isotopes of the radon nuclide as indicated in the alpha and electron source term sections. Photons associated with the radon isotopes as they occur in any decay chain are eliminated from the total summed photon yield for a given parent and therefore such contribution is not included in the tabular and spectral data. Additionally, note that there are several radionuclides that have spontaneous fission branches. Since a spontaneous fission event leads to many different daughter nuclides, the associated γ -rays will be very weak and therefore have not been included in the source term. The branch intensities of the Table 4-5 nuclides having spontaneous fission branches identified in the Table of Radioactive Isotopes are: ^{233}U ($1.3 \times 10^{-100}\%$), ^{238}Pu ($1.84 \times 10^{-7}\%$), ^{239}Pu ($4.4 \times 10^{-100}\%$), ^{241}Am ($4.1 \times 10^{-100}\%$), ^{242}Pu ($5.5 \times 10^{-49}\%$), and ^{243}Am ($2.2 \times 10^{-8}\%$). The contribution to the source term from the progeny of the spontaneous fission decays can safely be neglected due to the very low branching ratios. This is also effectively the case for the ^{252}Cf nuclide. There are no tabulated ^{252}Cf ENSDF data regarding the specific γ -rays and intensities of the daughters and it therefore has not been evaluated relative to a photon source term. This is of no great significance since there are only one or two drums listed in the TWDB database that indicate the presence of californium.

The photon source term specified for each parent/progeny chain includes all γ -rays in addition to x-rays arising from vacancies created in the K and L_1 atomic shells by internal conversion and electron-capture processes. The data have been processed into 50 keV energy bins as a reasonable compromise between data manipulation complications and data integrity as processed for input to photon shielding computations. In regard to the interpretation of the shielding calculation results, the source term does not include any consideration of source self-absorption, or for that matter, waste matrix attenuation of the source. This is primarily due to the fact that no valid uniformly-applicable information is available as to the source configuration and distribution within the waste matrix. Thus the source term data as presented is purely the theoretical photon yield from the parent/progeny source of interest at 15 years post purification. The subsequent data evaluator can apply corrections based on assumptions deemed reasonable or applicable for the case under study.

The results of the photon source term computations are shown in tabular form in Tables 4-21 through 4-37 (nuclide mass = 1.0 gram at $t = 0$). The data are in units of photons per second per 50 keV energy bin per gram parent/parent compound at 15 years from time zero or post purification. Each energy bin is represented in the tabular data by the bin energy midpoint in units of keV. For example, the energy bin spanning the 0-to-50 keV range is represented as the 25 keV bin, etc. The respective data is plotted in histogram form in Figures 4-3 through 4-19 with an ordinate scale of log base 10. The plotted data represent the number of photons per second per 50 keV interval at a 15 year decay time due to an initial time zero parent or parent compound mass of one gram. Note that using an ordinate scale of this nature is not precisely correct as photon/sec/gram/50 keV bin values less than 1.0 are not plotted. Nevertheless, such a representation is adequate for purposes of displaying the photon yield energy dependence.

Table 4-21. Tabular data for gamma spectrum of Am-241 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	5.21E+10	675	5.46E+05
75	4.45E+10	725	2.55E+05
125	3.49E+07	775	2.83E+04
175	5.15E+05	825	3.37E+03
225	1.13E+06	875	2.70E+03
275	1.45E+05	925	1.01E+03
325	1.10E+06	975	7.20E+02
375	5.65E+05	1,025	1.68E-06
425	8.62E+04	1,075	0.00E+00
475	2.43E+04	1,125	1.68E-06
525	1.04E+05		
575	1.60E+04		
625	8.40E+04		

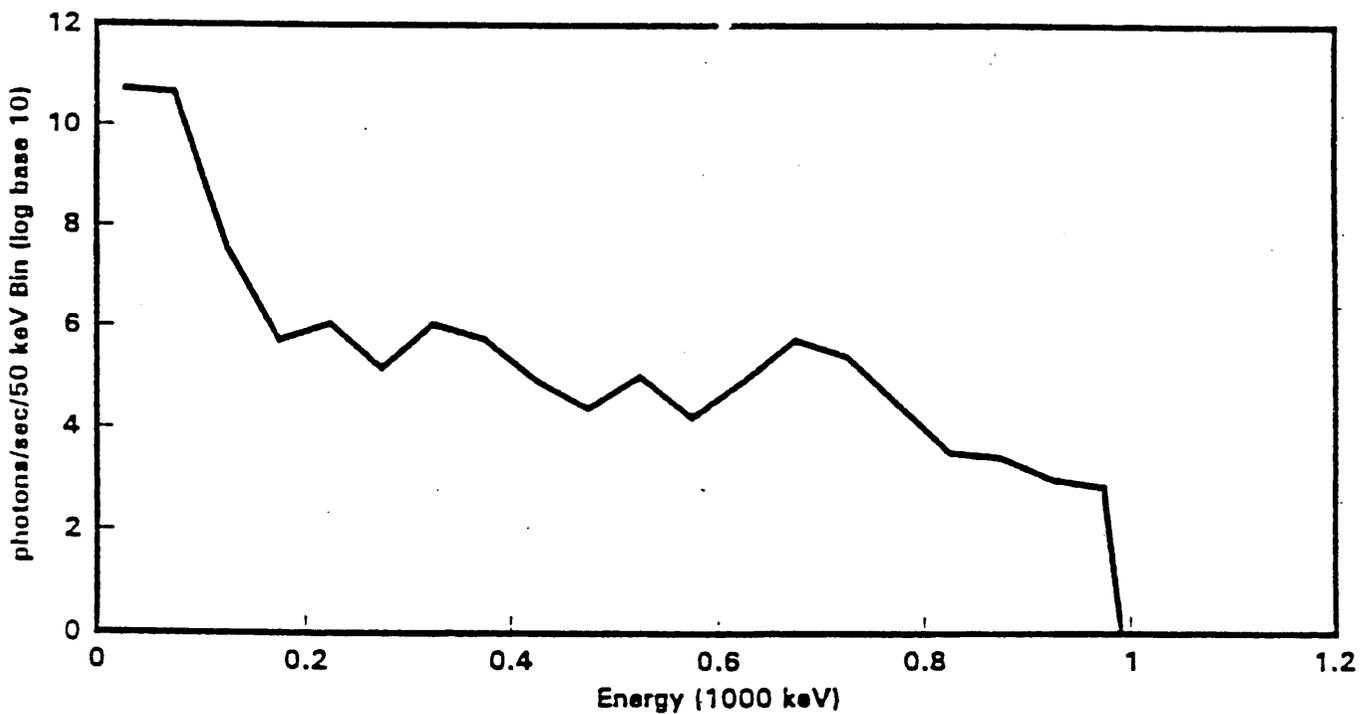


Figure 4-3. Gamma spectrum of Am-241 parent at 15 years post purification.

Table 4-22. Tabular data for gamma spectrum of Am-243 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	4.63E+09	575	7.48E-02
75	6.30E+09	625	2.42E+04
125	4.75E+09	675	6.99E+04
175	7.48E+06	725	2.73E-01
225	1.12E+09	775	5.02E-01
275	1.15E+09	825	2.15E-02
325	2.76E+08	875	4.09E-03
375	1.16E+05	925	1.36E-03
425	1.28E+06	975	3.69E-03
475	1.28E+06	1,025	3.87E-04
525	1.09E+05	1,075	1.45E-03

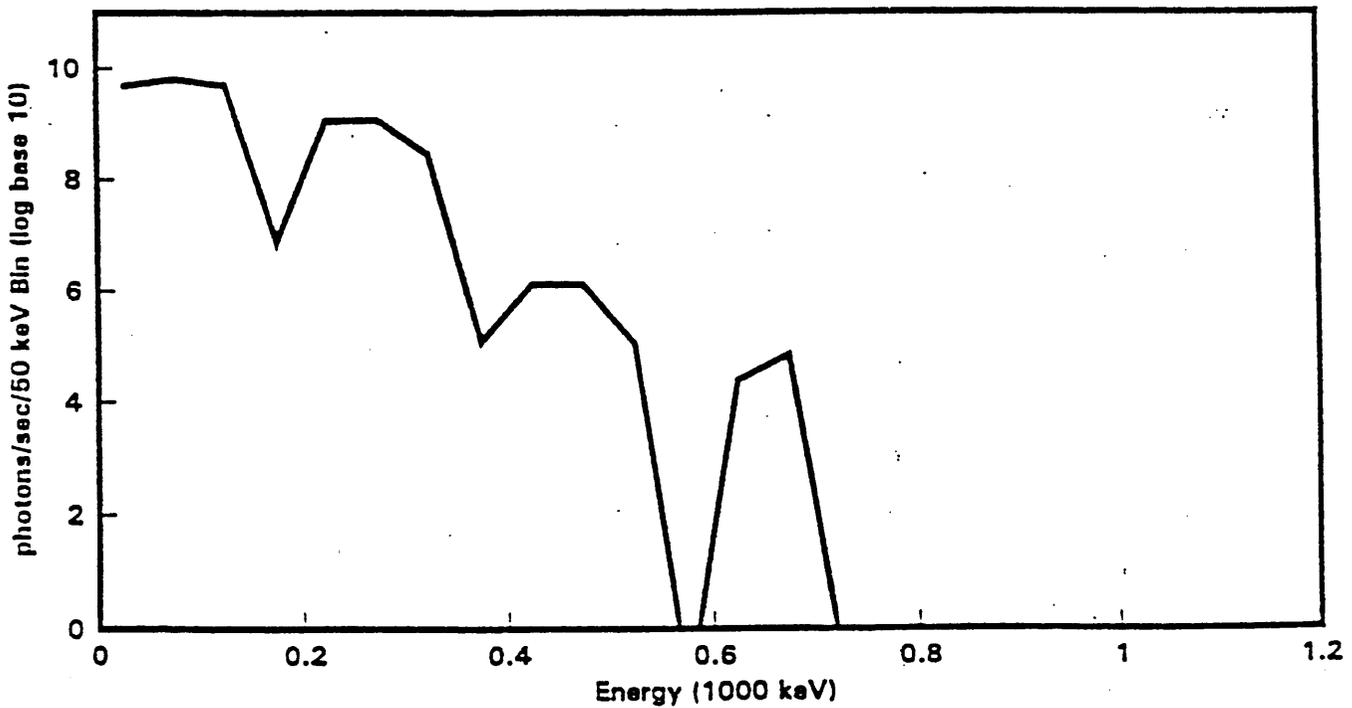


Figure 4-4. Gamma spectrum of Am-243 parent at 15 years post purification.

Table 4-23. Tabular data for gamma spectrum of Np-237 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.76E+07	675	5.16E-05
75	6.23E+00	725	4.73E-05
125	5.63E+05	775	0.00E+00
175	2.23E+05	825	0.00E+00
225	8.77E+04	875	3.57E-05
275	3.92E+03	925	0.00E+00
325	2.12E-01	975	0.00E+00
375	1.81E-02	1,025	1.42E-04
425	6.61E-04	1,075	0.00E+00
475	2.43E-03	1,125	1.42E-04
525	3.73E-04	1,175	0.00E+00
575	1.51E-04		
625	3.96E-05		

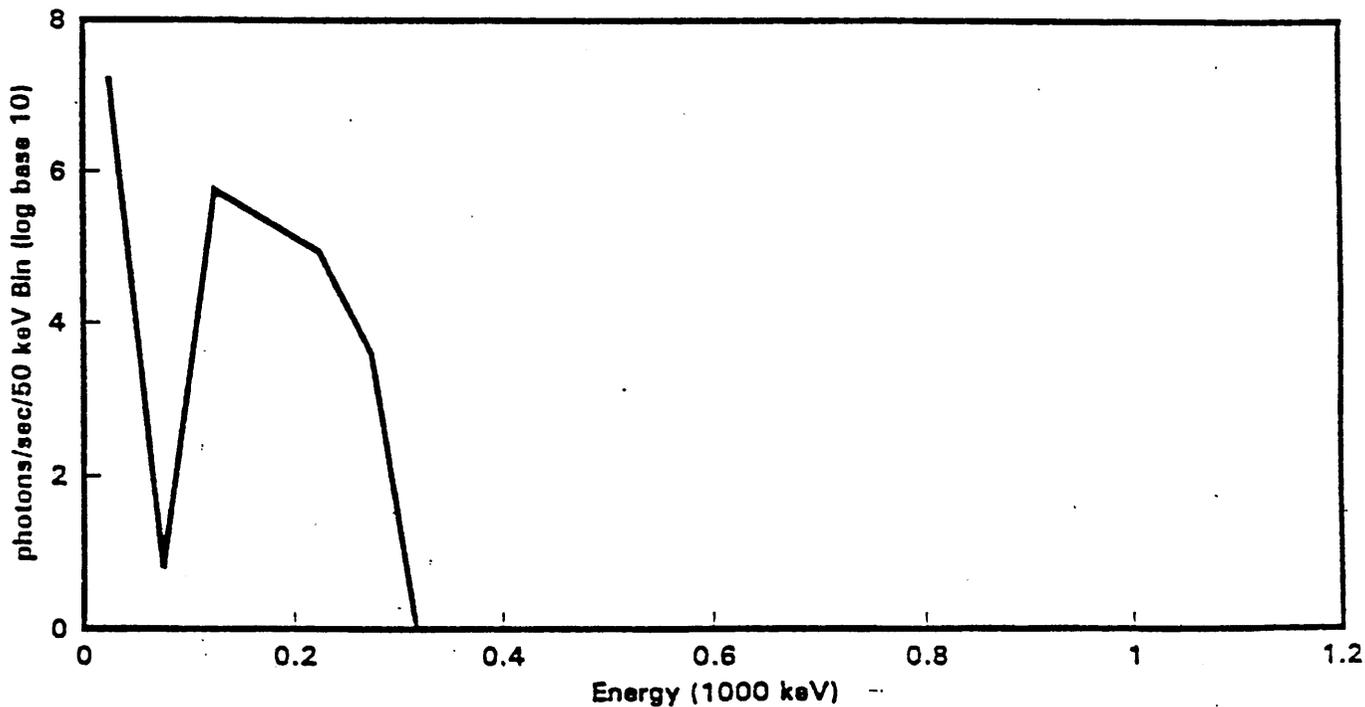


Figure 4-5. Gamma spectrum of Np-237 parent at 15 years post purification.

Table 4-24. Tabular data for gamma spectrum of Pu-236 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	2.49E+11	925	3.66E-08	1.825	9.22E+08
75	3.16E+11	975	1.32E+09	1.875	0.00E+00
125	6.08E+09	1.025	0.00E+00	1.925	0.00E+00
175	1.17E+09	1.075	6.68E+09	1.975	0.00E+00
225	3.68E+11	1.125	0.00E+00	2.025	0.00E+00
275	2.04E+10	1.175	7.89E+07	2.075	0.00E+00
325	2.50E+10	1.225	0.00E+00	2.125	0.00E+00
375	0.00E+00	1.275	1.47E+08	2.175	0.00E+00
425	6.31E+07	1.325	0.00E+00	2.225	0.00E+00
475	1.41E+08	1.375	1.97E+07	2.275	0.00E+00
525	6.43E+10	1.425	0.00E+00	2.325	0.00E+00
575	1.24E+10	1.475	0.00E+00	2.375	0.00E+00
625	2.23E+07	1.525	2.54E+09	2.425	0.00E+00
675	1.01E+08	1.575	0.00E+00	2.475	0.00E+00
725	6.20E+10	1.625	1.14E+10	2.525	0.00E+00
775	1.38E+10	1.675	6.16E+08	2.575	0.00E+00
825	1.13E+08	1.725	6.63E+06	2.625	2.93E-11
875	3.81E+10	1.775	0.00E+00	2.650	0.00E-00

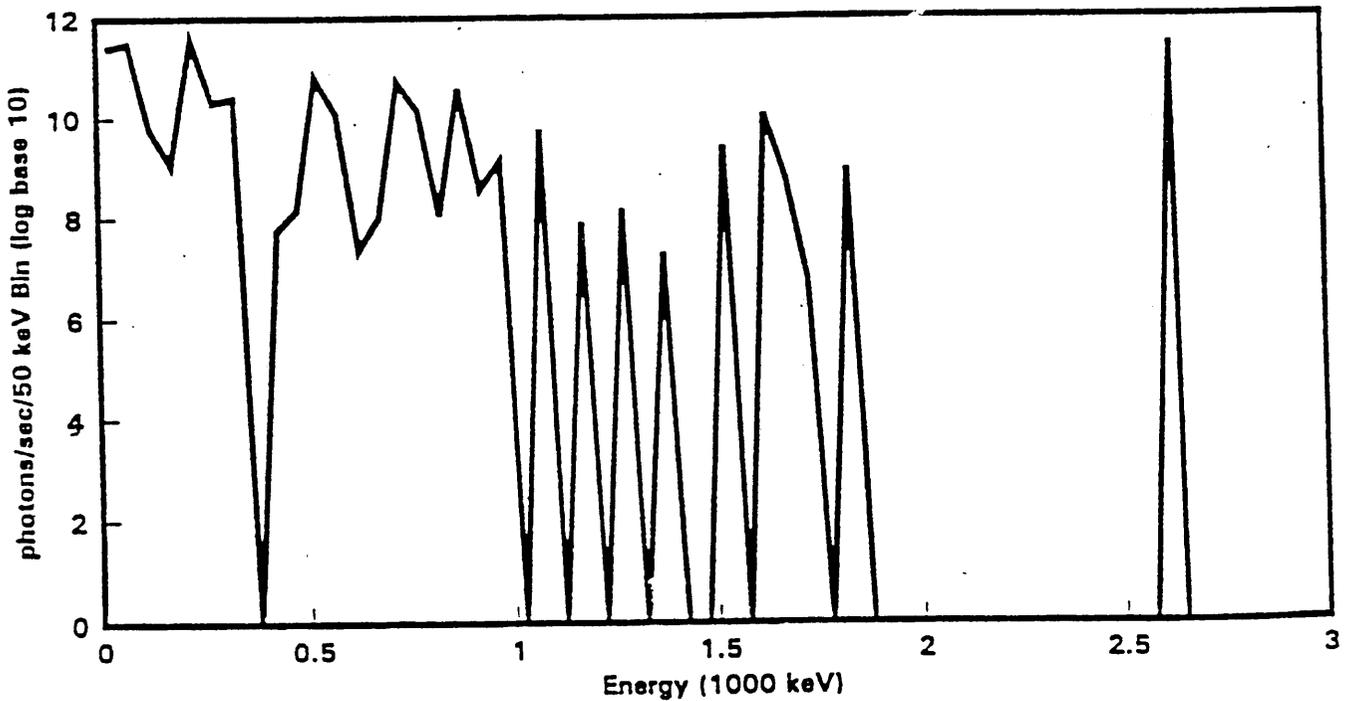


Figure 4-6. Gamma spectrum of Pu-236 parent at 15 years post purification.

Table 4-25. Tabular data for gamma spectrum of Pu-238 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	6.13E+10	625	2.17E-01
75	4.26E+07	675	2.71E-01
125	3.62E+05	725	4.67E+04
175	5.28E+06	775	2.12E+05
225	2.32E+04	825	6.95E+03
275	1.40E+03	875	1.89E+04
325	0.00E+00	925	9.59E+03
375	0.00E+00	975	4.50E+02
425	2.74E-05	1,025	9.33E+03
475	6.78E+00	1,075	5.93E+02
525	4.40E+00	1,125	0.00E+00
575	3.25E+00		

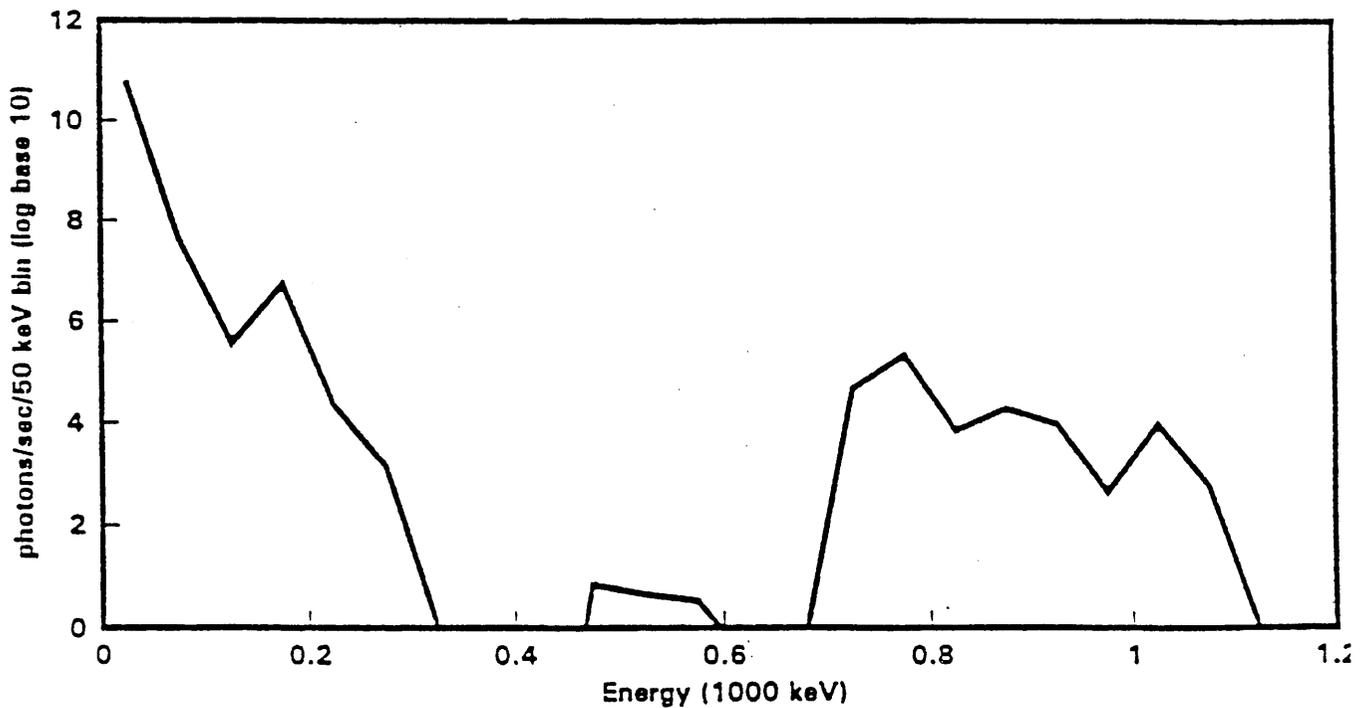


Figure 4-7. Gamma spectrum of Pu-238 parent at 15 years post purification.

Table 4-26. Tabular data for gamma spectrum of Pu-239 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	2.70E+05	575	5.32E+01
75	9.30E+05	625	7.93E+02
125	2.57E+05	675	5.03E+02
175	1.21E+04	725	1.94E+02
225	1.48E+04	775	3.57E+02
275	3.72E+03	825	1.53E+01
325	3.33E+04	875	2.91E+00
375	6.58E+04	925	9.64E-01
425	3.75E+04	975	2.62E+00
475	4.57E+03	1,025	2.75E-01
525	6.89E+00	1,075	1.03E+00

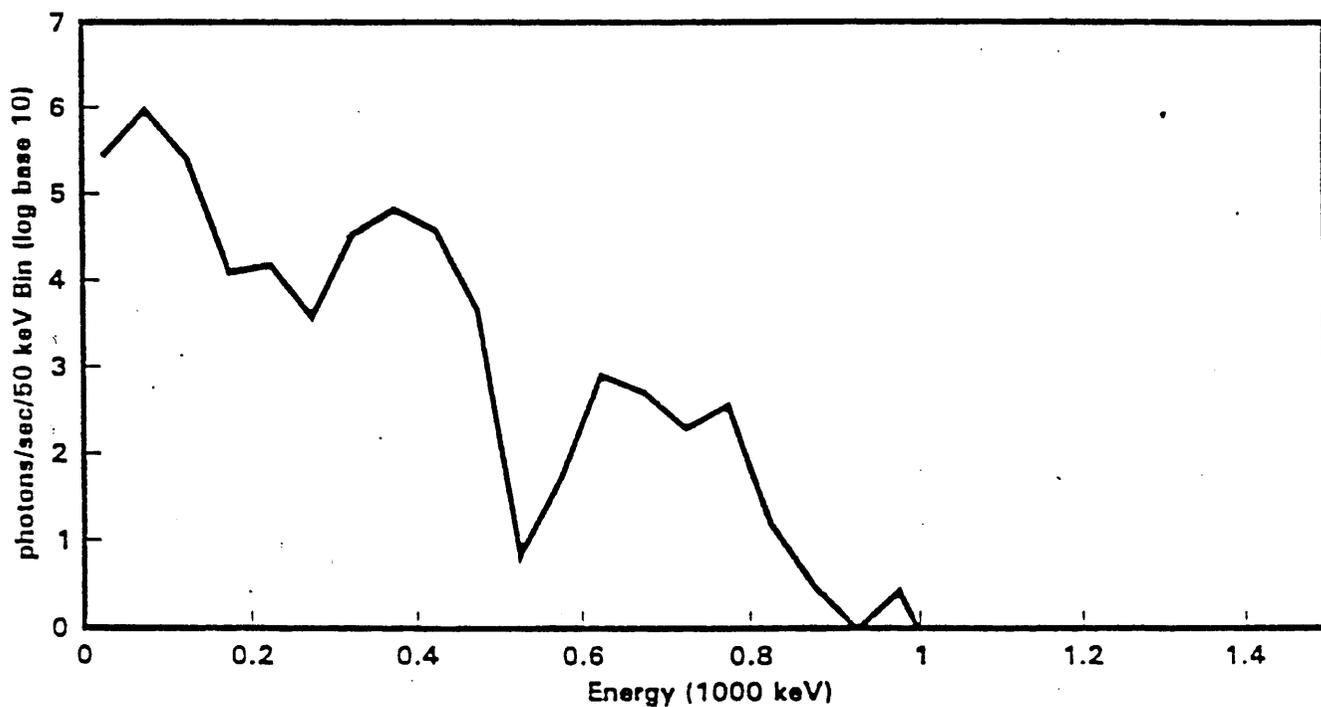


Figure 4-8. Gamma spectrum of Pu-239 parent at 15 years post purification.

Table 4-27. Tabular data for gamma spectrum of Pu-240 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	3.74E+06	525	1.18E+01
75	5.95E+03	575	0.00E+00
125	6.03E+05	625	1.03E+03
175	3.37E+04	675	2.85E+02
225	2.27E+03	725	0.00E+00
275	0.00E+00	775	0.00E+00
325	0.00E+00	825	0.00E+00
375	0.00E+00	875	4.69E+01
425	0.00E+00	925	0.00E+00
475	0.00E+00		

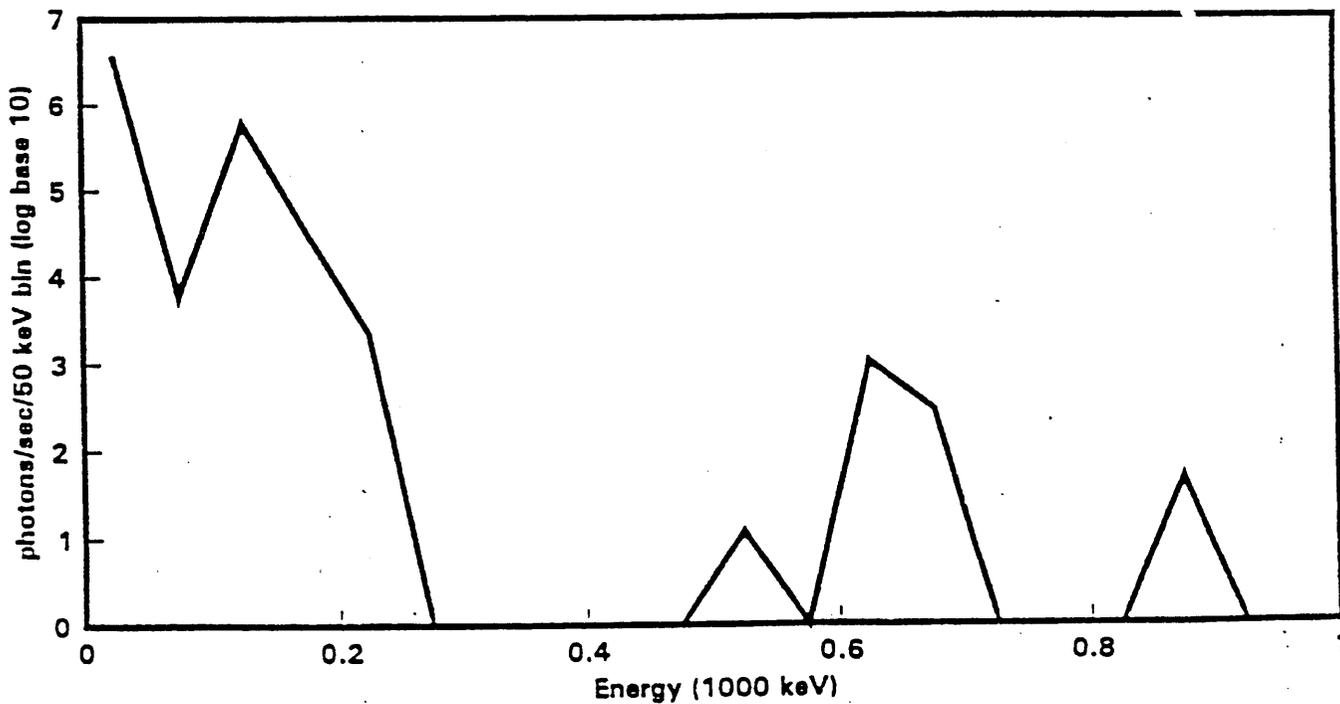


Figure 4-9. Gamma spectrum of Pu-240 parent at 15 years post purification.

Table 4-28. Tabular data for gamma spectrum of Pu-241 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	2.71E+10	675	2.84E+05
75	2.32E+10	725	1.32E+05
125	4.52E+07	775	1.47E+04
175	1.24E+06	825	1.75E+03
225	1.04E+07	875	1.41E+03
275	4.07E+05	925	5.23E+02
325	1.15E+06	975	0.00E+00
375	3.59E+05	1,025	3.39E-07
425	4.18E+04	1,075	0.00E+00
475	1.26E+04	1,125	3.39E-07
525	5.43E+04		
575	8.32E+03		
625	4.36E+04		

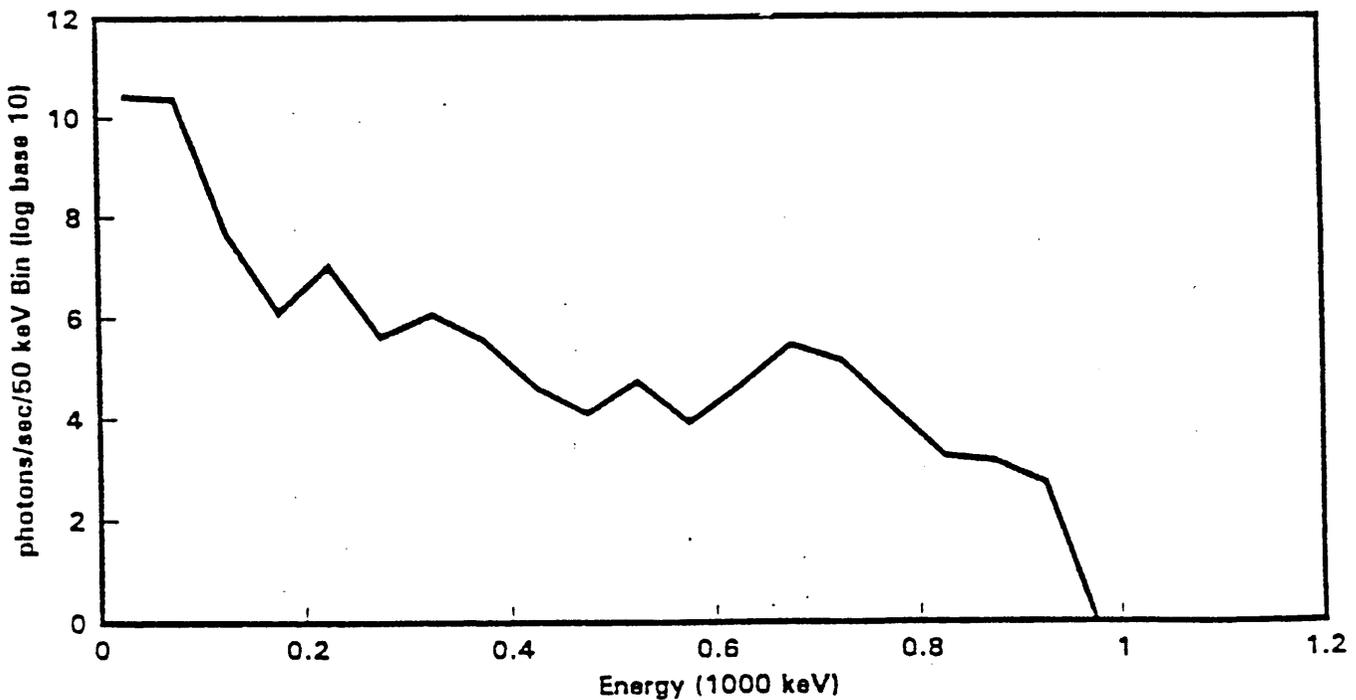


Figure 4-10. Gamma spectrum of Pu-241 parent at 15 years post purification.

Table 4-29. Tabular data for gamma spectrum of Pu-242 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.26E+07	375	0.00E+00
75	3.27E-02	425	1.82E-12
125	3.73E+03	475	1.18E-12
175	4.39E+02	525	8.75E-13
225	0.00E+00	575	5.83E-14
275	0.00E+00	625	7.29E-14
325	0.00E+00	675	1.09E-13

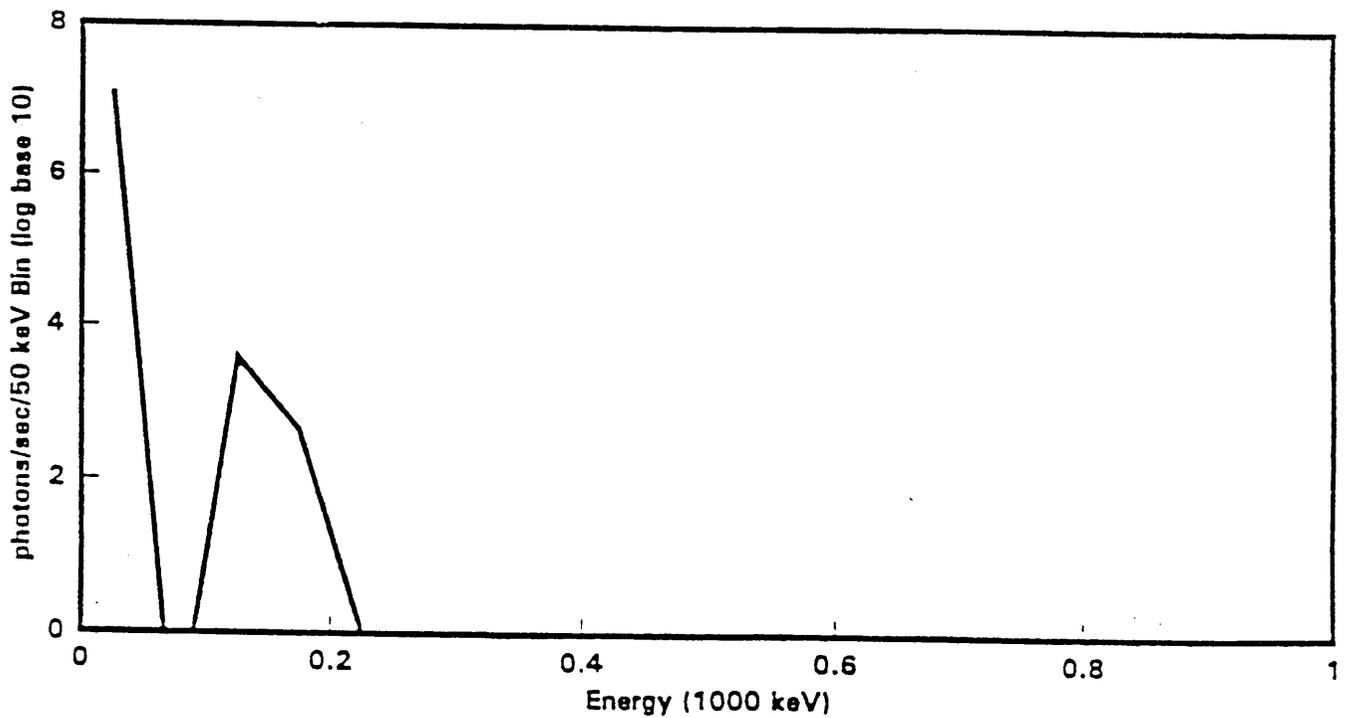


Figure 4-11. Gamma spectrum of Pu-242 parent at 15 years post purification.

Table 4-30. Tabular data for gamma spectrum of Ra-226 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-d	Bin Midpoint keV	Gamma Emission photons/sec-d	Bin Midpoint keV	Gamma Emission photons/sec-d
25	9.18E+09	1.125	5.88E+09	2.225	1.89E+09
75	9.84E+09	1.175	6.85E+08	2.275	1.38E+08
125	0.00E+00	1.225	2.43E+09	2.325	1.34E+07
175	0.00E+00	1.275	5.58E+08	2.375	7.04E+06
225	2.84E+09	1.325	9.07E+07	2.425	5.90E+08
275	7.87E+09	1.375	1.82E+09	2.475	7.80E+06
325	1.51E+08	1.425	1.48E+09	2.525	2.23E+06
375	1.40E+10	1.475	3.06E+07	2.575	1.49E+05
425	1.15E+08	1.525	1.12E+09	2.625	5.07E+05
475	5.44E+08	1.575	5.00E+08	2.675	1.34E+07
525	1.69E+08	1.625	7.06E+06	2.725	6.89E+05
575	1.81E+08	1.675	5.51E+08	2.775	1.19E+07
625	1.75E+10	1.725	1.15E+09	2.825	9.28E+06
675	6.55E+08	1.775	6.04E+09	2.875	6.04E+06
725	4.14E+08	1.825	9.54E+08	2.925	7.27E+06
775	2.47E+09	1.875	2.10E+08	2.975	9.33E+06
825	8.18E+08	1.925	1.93E+07	3.025	0.00E+00
875	0.00E+00	1.975	2.04E+06	3.075	1.04E+07
925	1.25E+09	2.025	2.89E+07	3.125	7.27E+05
975	0.00E+00	2.075	5.14E+07	3.175	7.52E+05
1.025	0.00E+00	2.125	4.95E+08	3.225	7.43E+04
1.075	0.00E+00	2.175	2.45E+07	3.275	3.73E+04
				3.325	0.00E+00

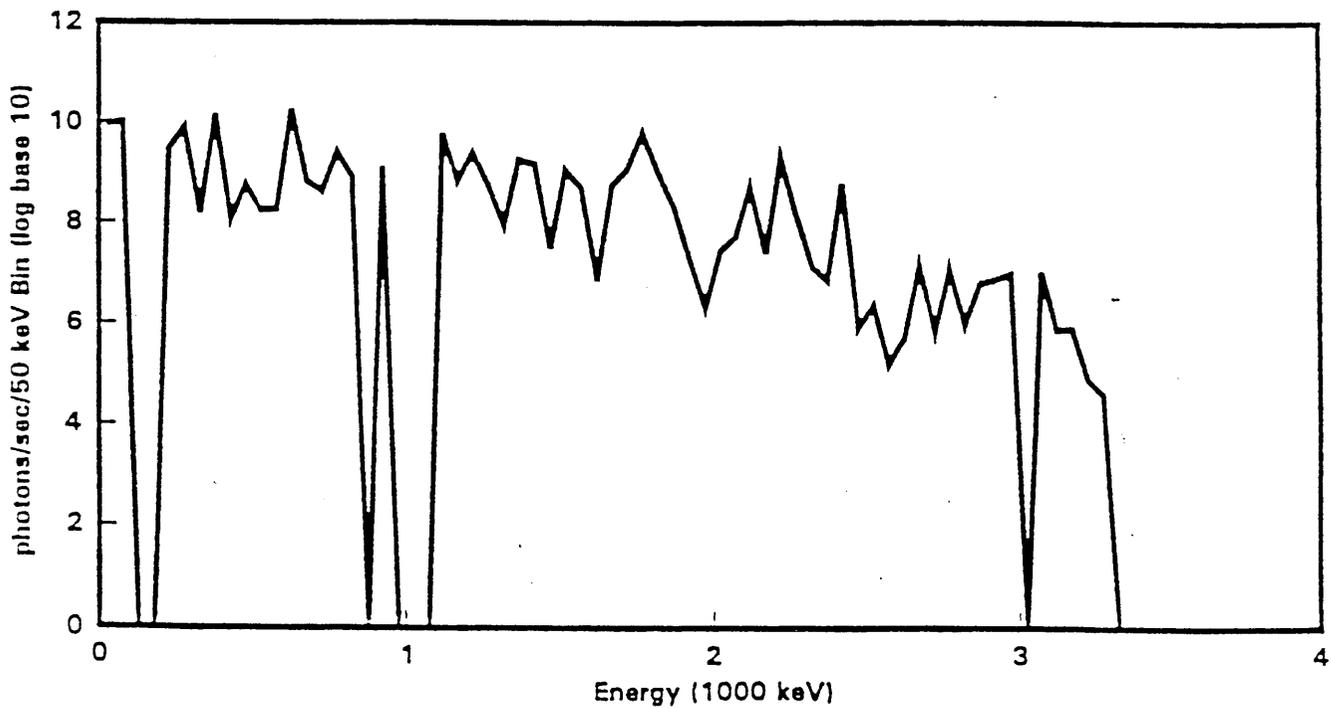


Figure 4-12. Gamma spectrum of Ra-226 parent at 15 years post purification.

Table 4-31. Tabular data for gamma spectrum of Th-230 parent at 15 years post purification.

Bin Midpoint eV	Gamma Emission photons/sec-g	Bin Midpoint eV	Gamma Emission photons/sec-g	Bin Midpoint eV	Gamma Emission photons/sec-g
25	1.06E+08	1.125	8.25E-05	2.225	2.85E+05
75	4.26E+08	1.175	9.61E+04	2.275	1.94E+04
125	3.72E+08	1.225	3.41E+08	2.325	1.87E+03
175	2.32E+08	1.275	7.82E+04	2.375	9.87E+02
225	3.93E+08	1.325	1.27E+04	2.425	8.28E+04
275	1.16E+08	1.375	2.55E+08	2.475	1.09E+02
325	2.11E+04	1.425	2.08E+08	2.525	3.13E+02
375	1.94E+08	1.475	4.28E+03	2.575	2.08E+01
425	1.82E+04	1.525	1.57E+08	2.625	7.11E+01
475	7.57E+04	1.575	7.01E+04	2.675	1.88E+03
525	2.38E+04	1.625	9.90E+02	2.725	9.38E+01
575	2.52E+04	1.675	7.73E+04	2.775	1.87E+03
625	2.44E+08	1.725	1.82E+08	2.825	1.30E+02
675	8.19E+04	1.775	8.47E+08	2.875	8.47E+02
725	8.81E+04	1.825	1.34E+08	2.925	1.02E+03
775	3.48E+08	1.875	2.94E+04	2.975	1.31E+03
825	1.14E+08	1.925	2.71E+03	3.025	0.00E+00
875	0.00E+00	1.975	2.87E+02	3.075	1.45E+03
925	1.78E+08	2.025	3.77E+03	3.125	1.02E+02
975	0.00E+00	2.075	7.21E+03	3.175	1.05E+02
1.025	0.00E+00	2.125	6.95E+04	3.225	1.04E+01
1.075	0.00E+00	2.175	3.44E+03	3.275	5.23E+00
				3.325	0.00E+00

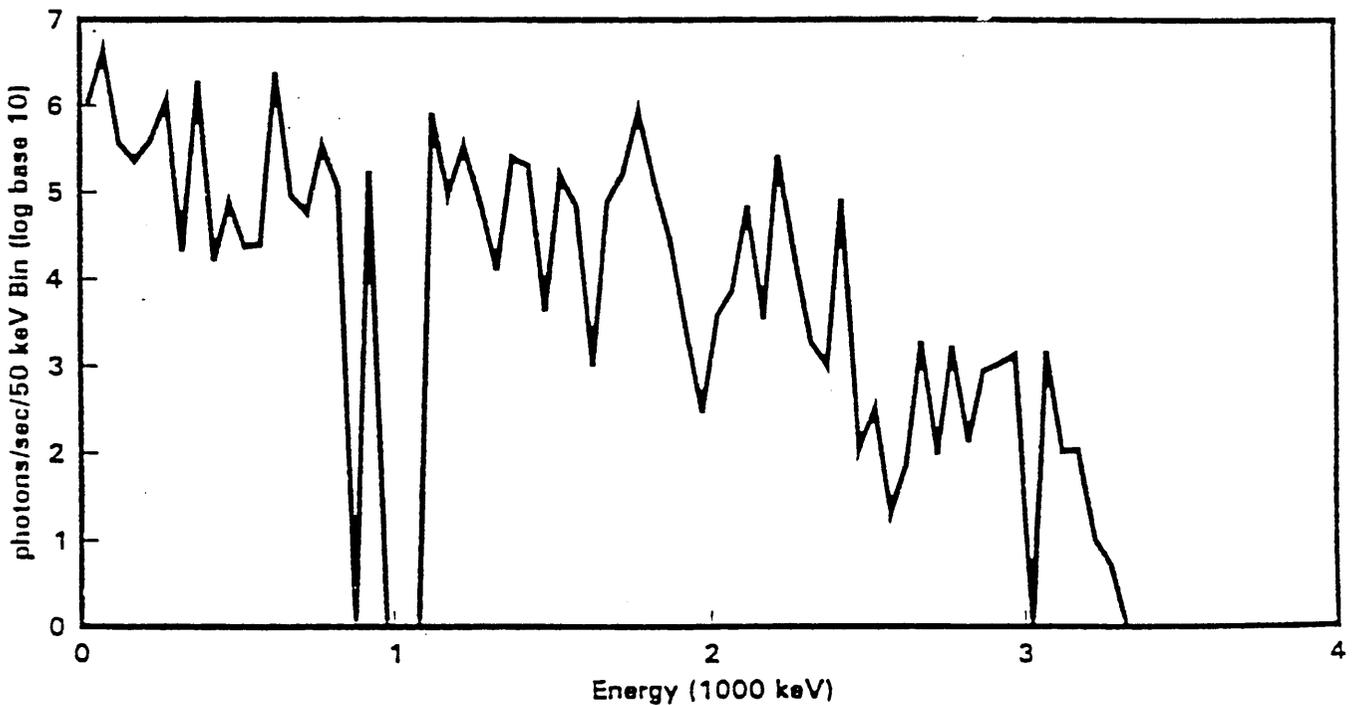


Figure 4-13. Gamma spectrum of Th-230 parent at 15 years post purification.

Table 4-32. Tabular data for gamma spectrum of Th-232 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.74E+03	725	4.37E+01	1,425	2.00E+00
75	4.28E+02	775	2.66E+02	1,475	7.49E+01
125	2.10E+02	825	1.17E+02	1,525	2.65E+01
175	5.20E+01	875	1.08E+01	1,575	1.59E+02
225	3.25E+02	925	1.04E+03	1,625	9.74E+01
275	1.45E+02	975	8.36E+02	1,675	1.28E+01
325	5.95E+02	1,025	1.01E+01	1,725	5.24E+00
375	4.95E+00	1,075	1.15E+01	1,775	2.08E+00
425	8.47E+01	1,125	1.69E+01	1,825	4.83E+00
475	1.72E+02	1,175	9.11E+00	1,875	4.99E+00
525	4.14E+01	1,225	2.54E+01	1,925	2.64E+00
575	1.07E+02	1,275	4.79E+00	1,975	3.31E+00
625	1.44E+01	1,325	1.91E+00	2,025	0.00E+00
675	4.13E+01	1,375	1.69E+00		

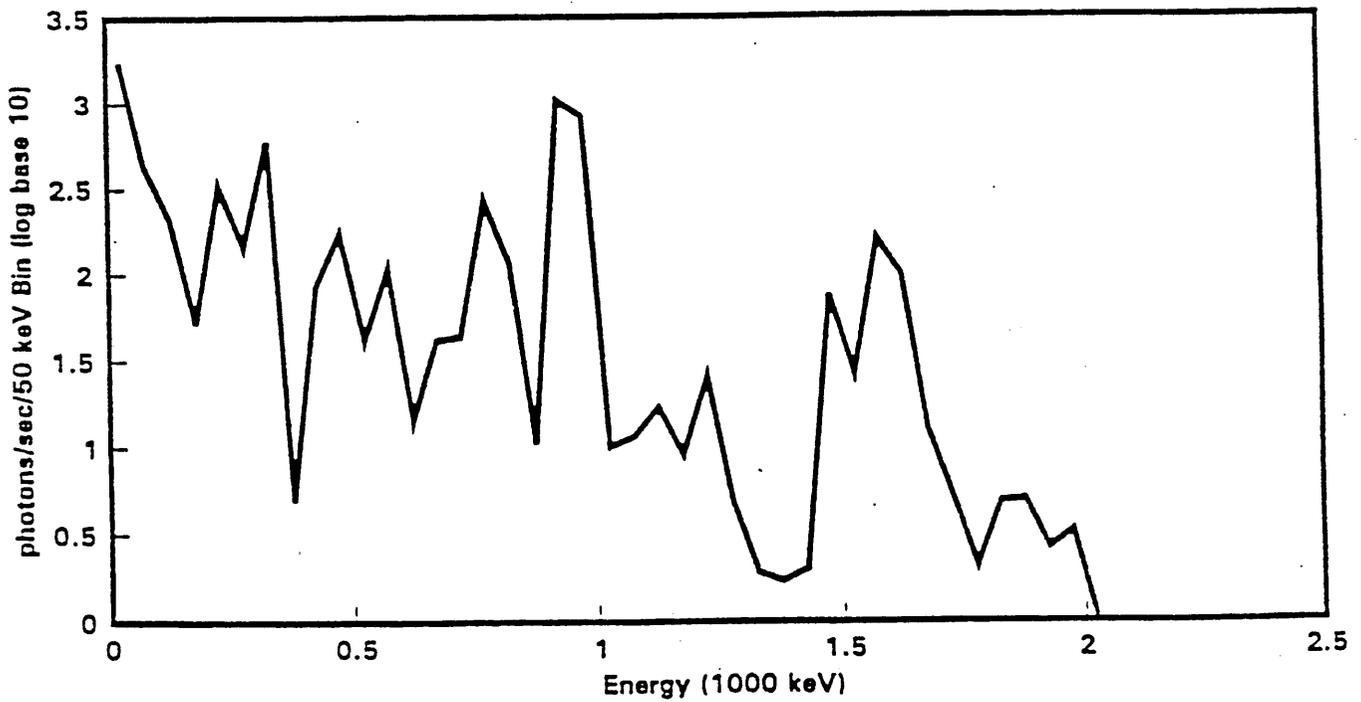


Figure 4-14. Gamma spectrum of Th-232 parent at 15 years post purification.

Table 4-33. Tabular data for gamma spectrum of U-233 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	2.50E+07	625	8.20E+00
75	3.82E+05	675	1.07E+01
125	1.53E+05	725	9.80E+00
175	8.26E+04	775	0.00E+00
225	1.40E+05	825	0.00E+00
275	3.47E+04	875	7.40E+00
325	4.41E+04	925	0.00E+00
375	4.12E+03	975	0.00E+00
425	8.27E+02	1,025	2.94E+01
475	8.80E+02	1,075	0.00E+00
525	1.31E+02	1,125	2.94E+01
575	3.12E+01	1,175	0.00E+00

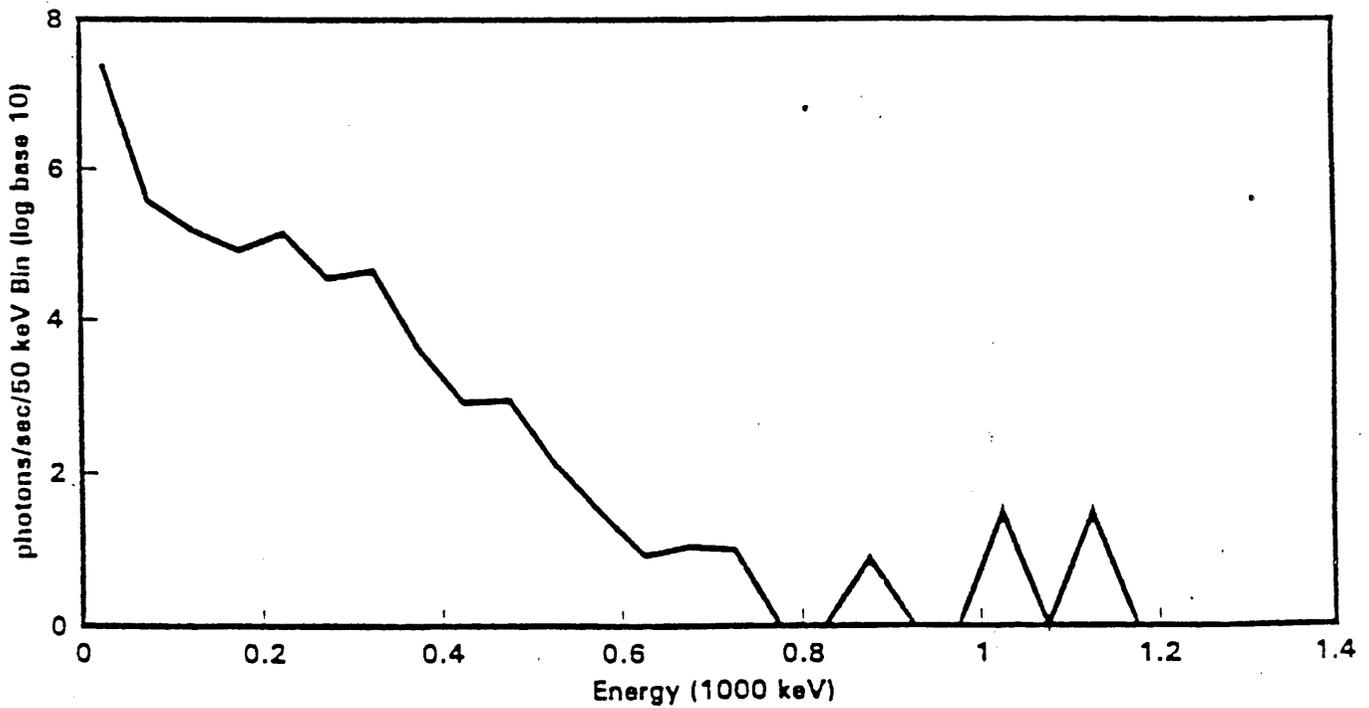


Figure 4-15. Gamma spectrum of U-233 parent at 15 years post purification.

Table 4-34. Tabular data for gamma spectrum of U-235 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.24E+05	575	5.03E-03
75	1.62E+04	625	1.62E-04
125	1.32E+04	675	5.27E-06
175	5.12E+04	725	3.20E-01
225	5.16E+03	775	4.80E-01
275	6.61E+01	825	4.15E-04
325	4.60E+01	875	4.60E-05
375	6.66E+01	925	1.18E-04
425	3.30E+00	975	9.16E-06
475	6.40E+00	1,025	2.63E-22
525	3.25E-01	1,075	0.00E+00

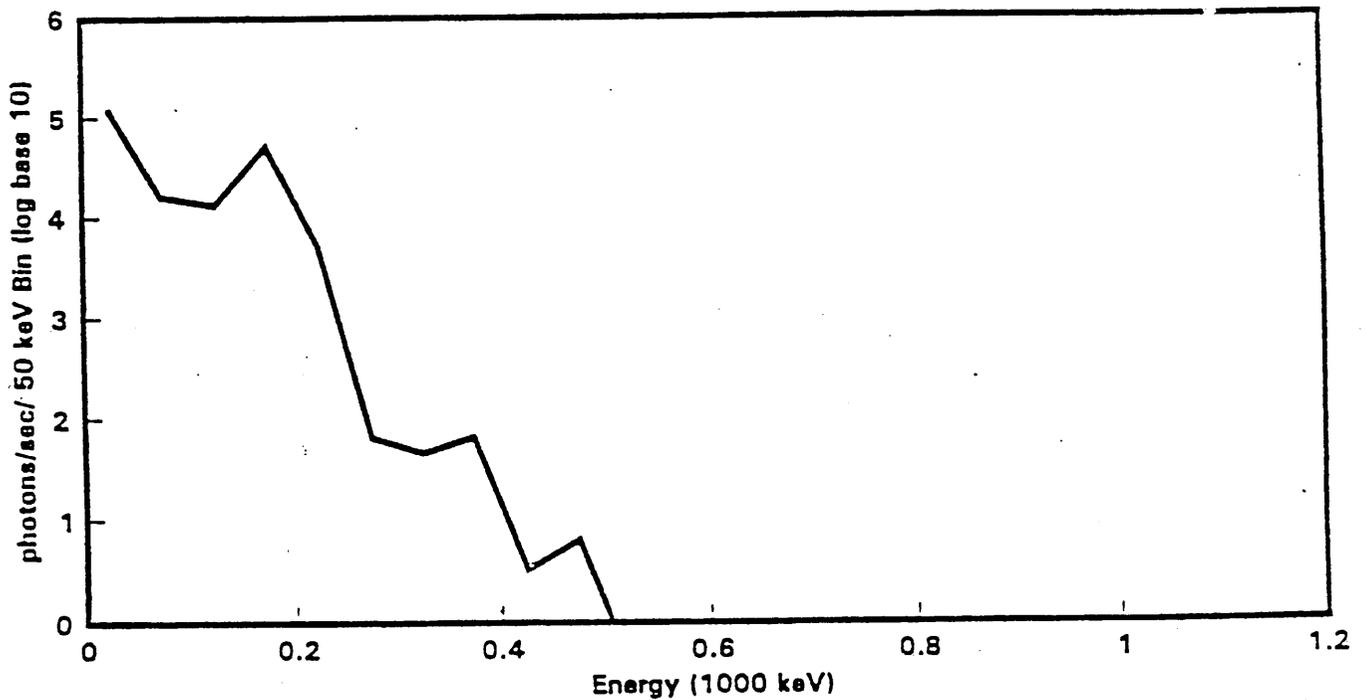


Figure 4-16. Gamma spectrum of U-235 parent at 15 years post purification.

Table 4-35. Tabular data for gamma spectrum of U-238 parent at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.63E+04	725	1.95E+03	1,425	7.59E+01
75	7.46E+03	775	1.39E+03	1,475	1.90E+02
125	4.49E+03	825	2.26E+03	1,525	6.32E+01
175	1.44E+03	875	4.22E+03	1,575	1.29E+02
225	2.22E+03	925	6.04E+03	1,625	6.96E+01
275	7.52E+02	975	1.14E+03	1,675	2.53E+02
325	1.96E+02	1,025	2.39E+02	1,725	2.79E+01
375	6.07E+02	1,075	1.26E+02	1,775	9.61E+01
425	1.56E+02	1,125	2.02E+02	1,825	1.14E+01
475	4.63E+02	1,175	6.82E+01	1,875	5.81E+01
525	6.77E+02	1,225	1.86E+02	1,925	1.05E+02
575	2.31E+03	1,275	1.39E+02	1,975	5.06E-01
625	6.19E+02	1,325	0.00E+00	2,025	0.00E+00
675	1.73E+03	1,375	6.38E+02		

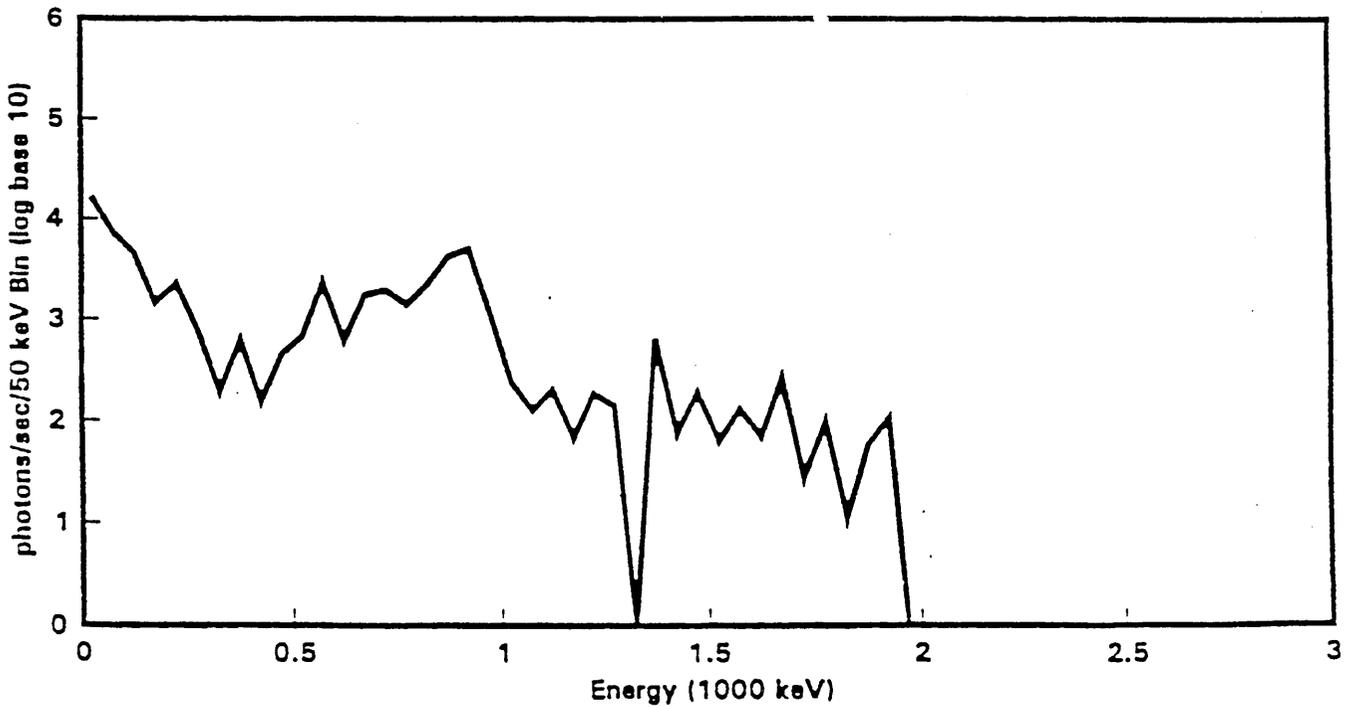


Figure 4-17. Gamma spectrum of U-238 parent at 15 years post purification.

Table 4-36. Tabular data for gamma spectrum of heat source plutonium at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	5.13E+10	925	8.38E+03	1.825	9.22E-02
75	1.29E+08	975	1.70E+03	1.875	0.00E+00
125	5.37E+06	1.025	7.79E+03	1.925	0.00E+00
175	4.41E+06	1.075	6.17E+03	1.975	0.00E+00
225	4.31E+05	1.125	1.36E-09	2.025	0.00E+00
275	2.37E+04	1.175	7.89E+01	2.075	0.00E+00
325	3.42E+04	1.225	0.00E+00	2.125	0.00E+00
375	1.06E+04	1.275	1.47E+02	2.175	0.00E+00
425	5.47E+03	1.325	0.00E+00	2.225	0.00E+00
475	8.37E+02	1.375	1.97E+01	2.275	0.00E+00
525	6.45E+04	1.425	0.00E+00	2.325	0.00E+00
575	1.24E+04	1.475	0.00E+00	2.375	0.00E+00
625	3.29E+02	1.525	2.54E+03	2.425	0.00E+00
675	1.31E+03	1.575	0.00E+00	2.475	0.00E+00
725	9.15E+04	1.625	1.14E+04	2.525	0.00E+00
775	1.91E+05	1.675	6.16E+02	2.575	0.00E+00
825	5.92E+03	1.725	5.83E+00	2.625	2.93E-05
875	5.39E+04	1.775	0.00E+00	2.650	0.00E+00

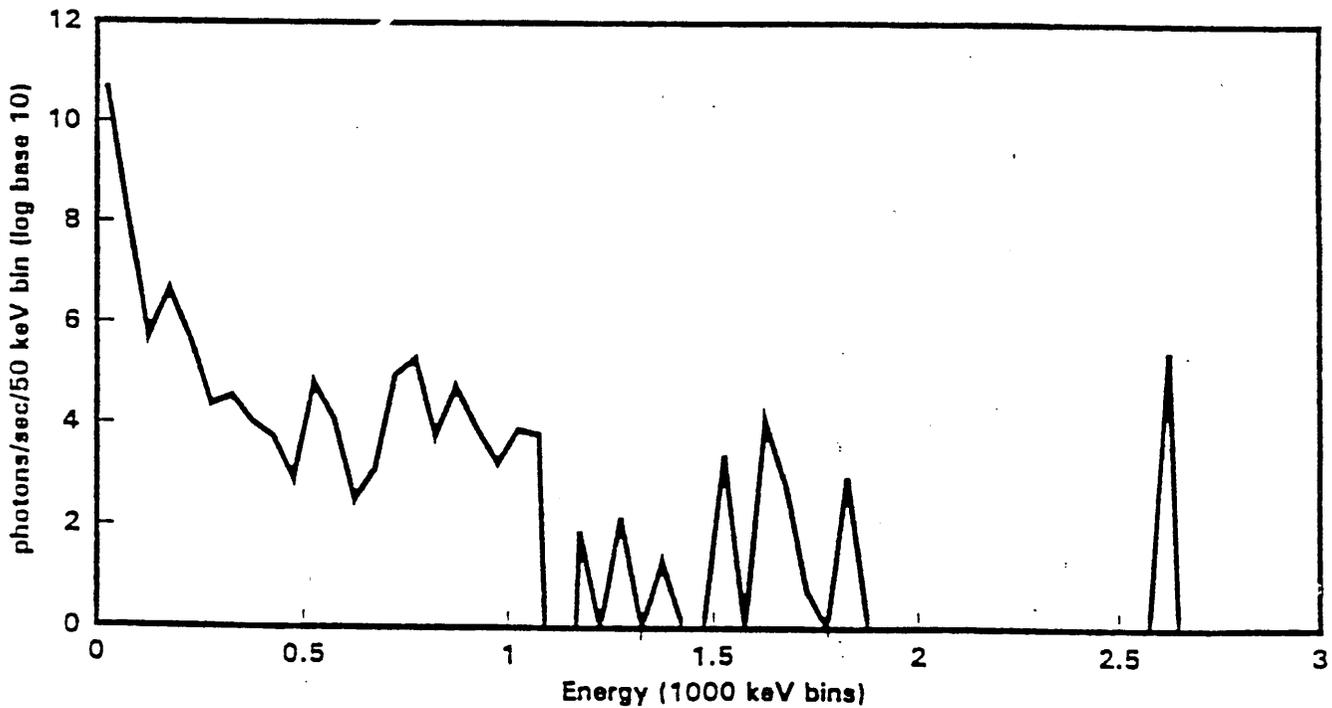


Figure 4-18. Gamma spectrum of heat source plutonium at 15 years post purification.

Table 4-37. Tabular data for gamma spectrum of weapons grade plutonium at 15 years post purification.

Bin Midpoint keV	Gamma Emission photons/sec-g	Bin Midpoint keV	Gamma Emission photons/sec-g
25	1.10E+08	675	1.56E+03
75	8.86E+07	725	6.89E+02
125	4.37E+05	775	4.16E+02
175	1.83E+04	825	2.18E+01
225	4.96E+04	875	1.30E+01
275	4.90E+03	925	4.03E+00
325	3.54E+04	975	2.66E+00
375	6.30E+04	1,025	1.38E+00
425	3.53E+04	1,075	1.04E+00
475	4.33E+03	1,125	1.49E-09
525	2.13E+02	1,175	0.00E+00
575	8.14E+01	1,225	0.00E+00
625	9.69E+02		

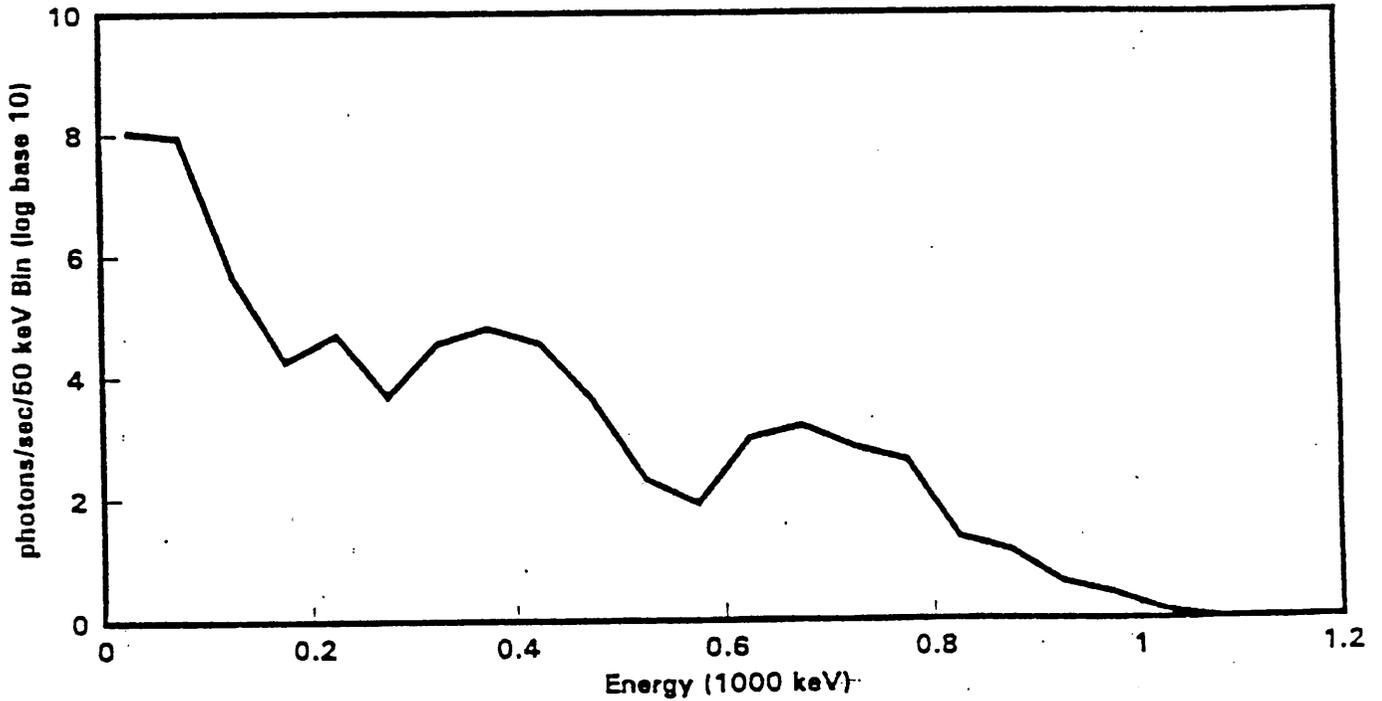


Figure 4-19. Gamma spectrum of weapons grade plutonium at 15 years post purification.

4.1.4 Neutron Data

Neutrons are generated in plutonium-bearing wastes from the spontaneous fission of the even-numbered plutonium isotopes and from interactions of the alpha decay particles with light elements in the waste matrix, i.e., (α, n) reactions. The number of neutrons generated per gram of waste-entrained plutonium therefore depends on both the isotopic composition of the plutonium and its chemical form. This condition complicates any effort to characterize the neutron source term since it is in most cases impossible to reliably know the plutonium chemical compounds existing in a given waste container sufficient to calculate a neutron source term. For this reason an alternate method has been devised with the intent of providing some bounds on the expected neutron source term. The information provided in this section is based on work by East (1993-1994).^{l,m}

The method is based on the evaluation of a database containing neutron measurement data on approximately 12,000 drums of RFP-generated waste acquired at the SWEPP waste examination facility.^m The resulting average neutron source term estimates are tabulated as a function of waste category, i.e., content code. The data is necessarily presented in this manner since the waste process generating a given content code is expected to contain similar plutonium chemical compounds, which in turn should have a similar neutron source term in units of neutrons/sec/gram-plutonium. In addition to the database analysis, calculations are performed to independently estimate the neutron source term based on tabulated neutron yields for the various plutonium and nonplutonium isotopes as a function of chemical form. This data is used to substantiate and to some extent validate the results obtained from the database analysis. The result of the above neutron source term estimation method is that it is dependent upon a waste form type. Therefore subsequent use of such data must be qualified relative to the waste form for which it has been specified. The calculational method is presented first, followed by the results of the neutron measurement database analysis.

4.1.4.1 Calculational Method. To support the calculational method, discussion is required on the origin of neutrons emitted from TRU waste. Additionally, estimates are made of the various radionuclidic and waste chemical forms such that neutron yields can be calculated.

Fast neutrons are emitted by plutonium as the result of the following processes:

- Spontaneous fissioning of the even-numbered isotopes (i.e., ²³⁸Pu, ²⁴⁰Pu, and ²⁴²Pu)
- Nuclear reactions induced by alpha particles from radioactive decay with light elements (Al, O, F, etc.) in intimate contact with the plutonium [(α, n) reactions]
- Fissions produced by the exposure of the odd-numbered isotopes (principally ²³⁹Pu) to thermal neutrons.

For most TRU waste forms containing plutonium, a negligible number of neutrons are produced from fissions induced by the neutrons resulting from radioactive decay (e.g., very little neutron multiplication will

l. L. V. East, *Neutron Source Terms for Rocky Flats Generated Waste at the INEL*, RWMC EDF-694, January 7, 1994.

m. L. V. East, *SWEPP Passive-Active Neutron Assay Database Description*, RWMC EDF-688, December 13, 1993.

occur). Therefore the primary sources of neutrons from waste are spontaneous fission and (α,n) reactions. Table 4-38 lists the spontaneous fission neutron yields for nonmultiplying samples, and neutron yields from (α,n) reactions for common plutonium chemical compounds. Yields from ^{241}Am are included in this table since this nuclide results from the radioactive decay of ^{241}Pu and is always present in plutonium-bearing waste.

As can be seen from Table 4-38, not only does the neutron emission rate per gram of source material depend on the isotopic composition, but it also is highly dependent on the chemical form due to the vastly different (α,n) yields of different elements. It also depends on the age of the material due to the build-up of ^{241}Am from the decay of ^{241}Pu (14.4 year half-life). Table 4-39 lists the expected neutron yields for some common isotopic compositions and chemical forms. Note that elevated concentrations of ^{241}Am will significantly increase the neutron output from oxides, fluorides, etc. but not from pure metals.

Tables 4-38 and 4-39 are provided to illustrate the nominal neutron emission rates expected per gram of isotope. The Table 4-39 WG Pu values for 90% PuO_2 /10% PuF_4 and PuO_2 on glass were calculated based on waste form source configuration estimates.⁴⁻³ As it will be shown, these values should be and are reasonably close to applicable neutron source term values as derived from the neutron measurement database analysis addressed in the next section.

Tabulated uranium neutron yields are provided as several uranium isotopes are identified in Table 4-5. As the RFP-generated waste is comprised primarily of WG Pu, there is no database of uranium mass measurements for comparison. Uranium will produce neutrons by the same mechanisms as plutonium; spontaneous fission, (α,n) reactions on light elements, and thermal neutron induced fission (the latter can, in most cases, be ignored unless there is a strong external source of neutrons present). With the exception of light element compounds containing significant quantities of the lighter uranium isotopes (232-234), neutron emission from uranium-bearing waste is generally insignificant. However, kilogram quantities of uranium will produce measurable neutron emissions for all enrichments (15 to 40 n/sec/kg for oxides and nitrates, 700 to 3000 n/sec/kg for fluorides).⁴⁻⁴ Neutron yields⁴⁻⁴ from uranium isotopes and their most common chemical compounds (UO_2 and UF_6) are shown in Table 4-40.

Other nuclides that may be present in retrievably-stored wastes (Table 4-5) may also produce neutron emissions, either by spontaneous fission or (α,n) reactions. The emission rates for the most important nonuranium and nonplutonium nuclides are listed in Table 4-41.

4.1.4.2 Neutron Measurement Database Analysis. A database containing information from the SWEPP passive/active neutron (PAN) drum assay system was used to calculate actual average neutron emission rates for many of the retrievably-stored RFP waste categories.ⁿ

n. L. V. East, *SWEPP Passive-Active Neutron Assay Database Description*, RWMC EDF-688, December 13, 1993.

Table 4-38. Neutron yields for plutonium isotopes and ²⁴¹Am.^a

Isotope	Neutron yields (n/sec/gm of isotope)				
	Spontaneous fission	(α, n) reactions ^b			
		Oxygen	Fluorine	Beryllium	Boron
²³⁸ Pu	2.5×10^3	1.5×10^4	2.8×10^6	2.5×10^7	5.4×10^6
²³⁹ Pu	2.3×10^{-2}	4.5×10^1	6.9×10^3	7.4×10^4	3.1×10^4
²⁴⁰ Pu	9.9×10^2	1.5×10^2	2.5×10^4	2.7×10^5	6.0×10^4
²⁴¹ Pu	$\sim 5 \times 10^{-2}$	1.4	2.1×10^2	2.5×10^3	6.1×10^2
²⁴² Pu	1.7×10^3	2.1	3.3×10^2	3.9×10^3	9.5×10^2
²⁴¹ Am	~ 1.3	2.7×10^3	5.5×10^5	3.5×10^6	7.6×10^5

a. EDF RWMC-694, 1/7/94.

b. Thin targets are assumed for oxygen and fluorine with atom ratios of two (PuO₂) and four (PuF₄), respectively. The beryllium and boron values are based on thick target yields from Reference 4-4.

Table 4-39. Representative neutron yields per gram Pu.^a

Material	Neutron yields (n/sec/gm-Pu)			
	Pure metal ^b	Oxide (PuO ₂)	90% PuO ₂ , 10% PuF ₄	PuO ₂ on glass ^c
WG Pu ^d	6.2×10^1	1.2×10^2	1.1×10^3	1.6×10^3
WG Pu with 50 wt% ²⁴¹ Am	6.4×10^1	3.0×10^3	6.2×10^4	3.8×10^4
Med Burnup Pu ^e	1.4×10^2	2.4×10^2	2.0×10^3	2.4×10^3
Heat Source Pu ^f	1.5×10^4	1.1×10^5	1.8×10^6	2.8×10^6

a. EDF RWMC-694, 1/7/94.

b. No significant neutron multiplication present.

c. Boro-silicate glass composed of 12% B₂O₃ (natural boron) and 88% SiO₂. 50% of the thick target yields⁴⁻³ were used for the B, O and Si contained in the glass.

d. "Weapons grade" (low burnup) plutonium; ~94% ²³⁹Pu, 6% ²⁴⁰Pu fifteen years after chemical purification.

e. Moderate burnup (~12 MWD/t) plutonium; ~87% ²³⁹Pu, 12% ²⁴⁰Pu fifteen years after chemical purification.

f. Approximately 85% ²³⁸Pu, 15% ²³⁹Pu, fifteen years after chemical purification.

Table 4-40. Neutron yields for uranium isotopes.^a

Isotope	Yields (n/sec/gm-isotope)		
	Spontaneous fission	(α ,n) reactions	
		UO ₂	UF ₆
²³² U	1.7	1.7×10^4	3.6×10^6
²³³ U	$<4.0 \times 10^{-4}$	4.7	7.9×10^2
²³⁴ U	7.6×10^{-3}	3.0	5.1×10^2
²³⁵ U	1.1×10^{-5}	7.2×10^{-4}	1.0×10^{-1}
²³⁶ U	4.4×10^{-3}	2.4×10^{-2}	3.3
²³⁸ U	1.4×10^{-2}	8.5×10^{-5}	1.1×10^{-2}

a. EDF RWMC-694, 1/7/94.

Note: ²³⁷U is not included in Table 4-40 since its beta decay does not give rise to neutron emissions.

Table 4-41. Neutron yields for other nuclides.^a

Isotope	Yields (n/sec/gm-isotope)		
	Spontaneous fission	(α ,n) reactions	
		Oxygen	Fluorine
²²⁶ Ra	0	$\sim 4.5 \times 10^2$	$\sim 7.5 \times 10^4$
²³⁰ Th	0	~ 8	$\sim 1.5 \times 10^3$
²³² Th	0	$<5 \times 10^{-5}$	$<8 \times 10^{-2}$
²³⁷ Np	0	~ 0.4	~ 50
²⁴³ Am	~ 4	$\sim 1.4 \times 10^2$	$\sim 2.5 \times 10^2$
²⁴² Cm	2.3×10^7	4.2×10^6	9.2×10^8
²⁴⁴ Cm	1.1×10^7	8.5×10^4	1.8×10^7
²⁵² Cf	2.3×10^{12}	6.9×10^5	1.5×10^8

a. EDF RWMC-694, 1/7/94.

The number of neutrons emitted per second by an individual drum was calculated from:

$$N_r = (T_r - B_{avg}) / \epsilon_n$$

where

T_r = Summed (total) count-rate from all neutron detectors in the drum assay system

B_{avg} = Average background rate determined from approximately 100 background measurements (28.13 counts/sec)

ϵ_n = Measured total neutron detection efficiency of the drum assay neutron counters (0.1263).^o

Note that no matrix corrections (for neutron absorption, etc.) have been applied.

The neutron emission rate value is next divided by the Pu mass to obtain the neutron source term in units of neutrons/second-gram Pu. Three mass values are available in the database:

- As declared by the waste generator (RFP)
- As determined by the SWEPP drum assay system in active mode
- As determined by the SWEPP drum assay system in passive mode.

Neutron emission rates were then obtained for each waste drum by dividing N_r by each of the three available masses. These values were then sorted and averaged for each waste category (content code) available in the sample set. The results are shown in Table 4-42 for each category in which at least five reliable mass measurements were obtained. The column labeled "Sample Size" gives the number of drums in each content code used in the average. Two average emission rates are shown for each waste category, one using generator RFP declared WG Pu mass values (labeled "RFP Mass") and the other (labeled "PAN Mass") based on SWEPP measurements; active neutron measurement mode results for sludges and passive neutron mode results are given for all other waste categories.

The values shown in Table 4-42 are consistent with the calculated values shown in the first two rows of Table 4-39, which are representative of source configurations of actual waste categories. There is also reasonable agreement (within a factor of two) between most emission rates based on RFP-supplied mass values and SWEPP-derived mass values; the most notable exception is the sludge content code 4 for which an order-of-magnitude difference exists.

^o G. K. Becker, *Pink Drum Calibration and Verification Calculations for FTC-CF-7284 Californium Source*, RWMC-EDF-547, May 1992.

Table 4-42. Average retrievably-stored waste neutron emission rates.^a

Content code	Sample size	Average (n/sec/gm-Pu)		Waste description
		RFP mass	PAN mass	
1	1393	9.4×10^3	7.4×10^3	First-stage sludge
2	28	3.8×10^3	1.3×10^3	Second-stage sludge
3	71	9.7×10^2	8.2×10^2	Organic setups, oil solids
4	123	3.2×10^3	4.4×10^2	Special setups (cemented)
7	361	2.4×10^3	8.4×10^2	Dry (cemented) sludge
111	22	1.1×10^3	5.3×10^2	Inorganic solids and wet sludges
115	10	2.2×10^2	2.1×10^2	Graphite waste
123	8	2.5×10^2	3.6×10^2	Leaded rubber
292	110	2.7×10^2	4.6×10^2	Cemented sludge
300	503	3.2×10^2	3.1×10^2	Graphite molds
303	18	1.7×10^2	2.2×10^2	Scarfed graphite chunks
320	51	6.0×10^2	1.1×10^3	Heavy non-SS metals (tantalum)
330	33	8.6×10^2	3.3×10^3	Dry paper and rags
335	7	1.1×10^3	2.0×10^3	Absolute 8 x 8 filters
336	46	7.9×10^2	1.1×10^3	Moist paper and rags
337	75	1.8×10^3	1.5×10^3	Plastics, Teflon, PVC
338	14	1.3×10^3	2.9×10^3	Insulation and CWS filter media
339	28	2.4×10^2	4.7×10^2	Leaded rubber gloves and aprons
371	30	4.2×10^2	6.8×10^2	Firebrick
374	5	1.3×10^3	5.1×10^2	Blacktop, concrete, dirt and sand
376	556	1.1×10^3	1.7×10^3	Cemented insulation/filter media
414	5	4.4×10^2	4.9×10^2	Direct oxide reduction salts
432	53	1.5×10^2	4.8×10^2	Leached and cemented resin
440	153	7.2×10^2	1.1×10^3	Glass
442	119	8.0×10^2	1.7×10^3	Leached Raschig rings
480	204	7.8×10^2	1.0×10^3	Unleached light non-SS metal
481	28	7.4×10^2	7.7×10^2	Leached light non-SS metal

a. EDF RWMC-694, 1/7/94.

The high average neutron rates for content code 1 waste can be attributed to the high ^{241}Am content of many of these waste drums. Many process residues (sludges) also contain significant amounts of light elements other than oxygen (B, Cl, F, etc.) in intimate contact with TRU alpha emitters resulting in elevated (α, n) production levels.

For RFP waste categories not covered in this sampling, a nominal upper limit of $\sim 10^4$ neutrons per second per gram of Pu is considered to be a safe assumption. The neutron emission rates for most wastes containing combustibles, metal scrap, etc. can be reasonably expected to lie in the range 2×10^2 to 2×10^3 .

4.2 Information Derived via RWMIS Analysis

The Radioactive Waste Management Information System (RWMIS) database is believed to contain the most accurate information on the total volume of waste stored at the TSA. This database contains information on many radionuclides, however, it reports information at the shipment level. The information provided in this section is based on work by Atwood and Schlafman (1993)^{4,5} and Morrell (1995).^p

Table 4-43 presents RWMIS derived nuclide information by shipment, volume and activity (decayed to December 1993).

RWMIS data was also analyzed for non-actinide activity for the categories of contact handled alpha low-level waste (CH-ALLW) and transuranic waste (CH-TRUW), and remote handled alpha low-level waste (RH-ALLW) and transuranic waste (RH-TRUW). The methods used for this analysis were to:

- Obtain shipment records from the RWMIS database for the TSA waste
- Separate into CH and RH shipment records by listed storage location, use ILTSF for known remote handled waste, and the rest as CH waste.
- Separate CH and RH shipment records by transuranic activity in terms of TRU nCi/g
 - use activity from DOE TRU defined nuclides; atomic number >92, half life > 20 years
 - use grams from shipment total weight
 - average nCi of shipment activity across entire weight of shipment
- Add up non-actinides per shipment
- Add up non-actinides per category
 - ALLW CH & RH
 - TRUW CH & RH.

Tables 4-44 and 4-45 summarize the non-actinide activity for the contact handled ALLW and TRUW, Tables 4-46 and 4-47 summarize the non-actinide activity for the known remote handled ALLW and TRUW stored at the ILTSF.

p. D. K. Morrell, *RWMIS Non-Actinides Summary*, EDF PSPI-015546-07, September 29, 1995.

Table 4-43. Nuclide summary by shipment, volume, and decayed activity.*

	Shipments	Volume of shipments (m ³)	Decayed activity to 2/17/93 (Ci)
Total	19521	64,746	372200.
TRU	19086	64,227	200600.
Non-TRU	19107	64,598	171600.
α-emitters	19168	64,658	202200.
β/γ-	18814	63,542	170000.
Fissionable	19166	64,657	353300.

By nuclide

Nuclide	Shipments	Volume of shipments (m ³)	Decayed activity to 2/17/93 (Ci)
Ac-277	1	0.21	0.04079
Am-241	18488	62,105	89780.
Am-242m	2	0.28	0.0003001
Am-243	22	175.41	0.3799
Ba-137m	459	1,452.0	2246.
Bi-212	54	395.0	26.55
Bi-214	0	0	0.0000000000
Bk-249	4	64.5	0.0005709
C-14	2	40.8	0.00004225
Ce-144	45	11.3	27.06
Cf-249	4	44.4	0.009729
Cf-252	9	116.1	0.004077
Cm-242	2	27.2	0.000001436
Cm-243	2	0.3	0.01531
Cm-244	15	138.0	539.0
Cm-246	3	41.8	0.001530
Cm-248	1	20.4	0.00000004170
Co-58	7	1.0	0.0000001101
Co-60	19	24.0	94.30
Cr-51	0	0	0.0000000000
Cs-134	34	9.3	110.7
Cs-137	167	173.7	2003.
Eu-150	0	0	0.0000000000
Eu-152	9	129.5	0.06756
Eu-154	15	114.3	0.7104
Eu-155	10	5.8	0.1863
Fe-55	4	41.0	1.132
Fe-59	0	0	0.0000000000
H-3	5	151.8	0.7978
Kr-85	2	0.3	6.857

Table 4-43. (continued).

	Shipments	Volume of shipments (m ³)	Decayed activity to 2/17/93 (Ci)
MAP ^b	36	290.6	1.280
MFP ^c	304	1,322.4	483.3
Mn-54	26	4.3	0.2287
Nb-95	0	0	0.0000000000
Ni-63	3	20.7	3.572
Np-237	38	368.8	0.3552
Pa-233	0	0	0.0000000000
Pb-210	1	0.2	0.01756
Pb-212	54	394.7	26.55
Pb-214	0	0	0.0000000000
Pm-147	3	0.5	27.26
Po-212	54	394.7	17.01
Po-214	0	0	0.0000000000
Po-216	54	394.7	26.55
Po-218	0	0	0.0000000000
Pr-144	45	11.3	27.18
Pu-236	299	213.5	0.01479
Pu-238	18400	62,764.7	60800.
Pu-239	19059	64,219.7	40150.
Pu-240	18881	62,665.5	9825.
Pu-241	18386	61,736.1	161100.
Pu-242	18329	61,766.6	0.9451
Ra-224	54	394.6	26.55
Ra-226	2	0.4	0.04790
Ra-228	1	0.2	0.03062
Rh-106	0	0	0.0000000000
Rn-220	54	394.7	26.55
Rn-222	0	0	0.0000000000
Ru-106	13	7.1	0.1865
Sb-125	11	5.9	1.647
Sr-90	32	8.9	1778.
Ta-182	1	0.1	0.00001548
Tc-99	3	24.0	0.001760
Th-228	54	394.7	26.55
Th-230	1	20.4	0.01998
Th-232	105	717.2	0.3301
Th-234	0	0	0.0000000000

Table 4-43. (continued).

	Shipments	Volume of shipments (m ³)	Decayed activity to 2/17/93 (Ci)
TI-208	54	394.7	9.540
U-228	0	0	0.00000000000
U-232	54	394.7	26.04
U-233	152	1,585.7	898.5
U-234	18410	63,005.0	5.778
U-235	1107	8,808.3	0.06669
U-236	31	285.1	0.001199
U-238	331	919.7	0.1171
Unid β/γ ^d	6	1.3	12.44
Y-90	334	1,331.0	2019.
Zn-65	2	40.8	0.00000001868
Zr-95	8	1.6	0.00000000234
<u>By location</u>			
<u>Location^e</u>			
TSA			
Total	19179	64,669	363700.
TRU	18744	64,150	200500.
Non-TRU	18771	64,552	163200.
ILTSF			
Total	342	77.2	8489.
TRU	342	77.2	100.3
Non-TRU	336	75.8	8388.
<u>By waste generator</u>			
<u>Generator</u>			
ALE	407	1,531.0	6002.
ANL	227	43.3	6812.
ARA	4	10.1	11.94
BCL	13	214.4	120.6
BEN	1	0.2	18.48
BET	78	433.2	1586.
CFA	2	0.2	0.04360
CPP	29	48.7	1330.
D+D	1	0.2	2.488
LOF	1	0.2	1.189
MRC	446	3,895.4	61000.
NRF	37	7.0	428.5
RFO	17960	54,167.8	280500.

Table 4-43. (continued).

	Shipments	Volume of shipments (m ³)	Decayed activity to 2/17/93 (Ci)
TAN	5	0.9	16.00
TRA	42	10.1	836.7
WMC	268	4,383.5	13480.

a. The activities are rounded off to four significant digits, EGG-RAAM-10741, April 1993.

b. "Mixed Activation Products," treated as C0-60.

c. "Mixed Fission Products," treated as a mixture of half Cs-137 and half Sr-90.

d. "Unidentified β/γ -emitters," treated as Cs-137.

e. The locations given as text in the data base are the Transuranic Storage Area (TSA), and the Intermediate Level Transuranic Storage Facility (ILTSF). ILTSF is the designated location for all remote-handled waste. In this table, the designation TSA therefore means all of the Transuranic Storage Area except ILTSF. Locations outside of the Transuranic Storage Area, such as Pad A and the Burial Ground Pit Air Support Building, are not considered here.

Table 4-44. Contact handled ALLW non-actinide activity.^a

Generator	Number of shipments	TRU actinides	nCi TRU actinide/ gram of waste	Non-actinide	Non-actinide activity (Ci)
ALE	14	Np-237	<=100	Eu-150	4.50e-05
		Pu-238		Eu-152	4.80e-04
		Pu-239		Eu-154	3.00e-06
		Pu-240			
		Am-241			
ANL	5	Cm-246	<=100	Cr-51	1.45
		Np-237		Mn-54	0.14
		Pu-239		Co-58	0.15
		Pu-240		Co-60	2.80
				Sr-90	0.30
				Cs-137	0.42
				Ce-144	0.42
				MAP ^b	0.58
	MFP ^c	0.45			
BET, ANL	No non-actinides were reported in the BETANL waste.				
CPP	No non-actinides were reported in the CPP waste.				
NRF	3	Pu-238	<=100	Cs-137	2.47
		Pu-239		MFP	4.47
		Pu-240			
		Pu-242			
TRA	2	Pu-239	<=100	Eu-152	0.34
				Total:	13.99

a. EDF PSPI-015546-07, 9/29/95.

b. Mixed activation products (MAP) treated as C0-60.

c. Mixed fission products (MFP) treated as a mixture of half Cs-137 and half Sr-90.

Table 4-45. Contact handled TRUW non-actinide activity.^a

Generator	Number of shipments	TRU actinides	nCi TRU actinide/ gram of waste	Non-actinide	Non-actinide activity (Ci)				
ALE	58	Np-237 Pu-238 Pu-239 Pu-240 Pu-242 Am-241 Cm-246	>100	H-3	2.20e-02				
				C-14	4.23e-05				
				Fe-55	6.11e-04				
				Co-60	5.00e-04				
				Ni-63	1.00e-04				
				Zn-65	1.10e-03				
				Tc-99	3.70e-04				
				Cs-137	1.08				
				Eu-152	1.09e-03				
				Eu-154	7.90e-05				
				MFP ^b	142.52				
				ANL	37	Pu-239 Pu-240 Pu-242	>100	Co-58	0.68
								Co-60	3.40
Ru-106	9.90e-04								
Cs-134	1.24e-04								
Cs-137	3.00								
Ce-144	5.69e-04								
Eu-155	2.99e-05								
MAP ^c	1.17								
MFP	2.48								
UN-ID-B+G	1.40								
BET, ANL	No non-actinides were reported in the BETANL waste.								
CPP	No non-actinides were reported in the CPP waste.								
NRF	1	Pu-238 Pu-239 Pu-240 Pu-242	>100	MFP	4.20				
				TRA	6	Pu-238 Pu-239 Pu-240 Pu-242 Am-241 Am-243	>100	Co-60	185.80
								Zr-95	66.8
								Tc-99	2.80e-03
Cs-137	65.30								
Ce-144	8.60								
Pm-147	928.00								
UN-ID-B+G	13.49								
				Total	1,427.95				

a. EDF PSPI-015546-07, 9/29/95.

b. Mixed fission products (MFP) treated as a mixture of half Cs-137 and half Sr-90.

c. Mixed activation products (MAP) treated as Co-60.

Table 4-46. Remote handled ALLW non-actinide activity.^a

Generator	Number of shipments	TRU actinides	nCi TRU actinide/ gram of waste	Non-actinide	Non-actinide activity (Ci)
ALE	21	Pu-239 Pu-240	<=100	Cs-137	13.98
ANL	3	Pu-239 Pu-240	<=100	Mn-54 Co-58 Sr-90 Cs-134 Cs-137 Ce-144 MFP ^b	7.00 7.00 2.40 1.20 4.40 7.00 1.00
BET, ANL	No non-actinides were reported in the BETANL waste.				
CPP	No non-actinides were reported in the CPP waste.				
NRF	6	Pu-238 Pu-239 Pu-240 Pu-242	<=100	MFP	2.06
TRA	No non-actinides were reported in the TRA waste.				
				Total	46.04

a. EDF PSPI-015546-07, 9/29/95.

b. Mixed fission products (MFP) treated as a mixture of half Cs-137 and half Sr-90.

Table 4-47. Remote handled TRUW non-actinide activity.^a

Generator	Number of shipments	TRU actinides	nCi TRU actinide/ gram of waste	Non-actinide	Non-actinide activity (Ci)
ALE	245	Np-237 Pu-239 Pu-240	>100	Cs-137 MFP ^b	88.97 346.98
ANL	29	Am-241 Np-237 Pu-239 Pu-240	>100	Cr-51 Mn-54 Co-58 Fe-59 Co-60 Sr-90 Nb-95 Zr-95 Ru-106 Cs-134 Cs-137 Ce-144 MAP ^c MFP ^b	7.01 108.40 105.44 5.34 23.86 1,684.64 0.72 0.43 3.00 870.97 1,759.34 3,863.93 4.00 6.00
BET, ANL	2	Np-237 Pu-238 Pu-239 Pu-240 Pu-242 Am-241 Am-242M Am-243 Cm-243	>100	Fe-55 Co-60 Ni-63 Kr-85 Sr-90 Y-90 Rh-106 Ru-106 Sb-125 Cs-134 Cs-137 Ba-137M Ce-144 Pr-144 Pm-147 Ta-182	3.86 16.78 3.69 9.36 101.75 101.75 1.30 1.30 5.31 34.90 102.31 97.33 15.64 15.64 84.13 0.74
CPP	10	Pu-238 Pu-239 Pu-240 Pu-242 Am-241	>100	Sr-90 Ru-106 Sb-125 Cs-134 Cs-137 Ce-144 Eu-154 Eu-155	326.55 101.07 0.78 22.55 324.78 3.89 1.56 0.78
NRF	20	Pu-238 Pu-239 Pu-240 Pu-242	>100	MFP ^b	78.45
TRA	No non-actinides were reported in the TRA waste.				
				Total:	10,335.23

a. EDF 015546-07, 9/29/95.

b. Mixed fission products (MFP) treated as a mixture of half Cs-137 and half Sr-90.

c. Mixed activation products (MAP) treated as Co-60.

4.3 Refinement of Nonactinide Nuclide Inventory Using Information from Other Sources

The shipping records and their compilation in the INEL databases often provide incomplete information on the radionuclides in the waste. Several other sources of information were investigated to obtain data on the identity and activity of nonactinide radionuclides. This information is discussed in the following sections. The results are given in terms of the radioactivities that need to be added to the RWMIS derived inventory for each type of waste. Table 4-48 presents a summary refined inventory for these select nuclides. Section 4.3.1, 4.3.2, and 4.3.3 provide additional information on derivation of Table 4-48 values. The information provided in this section is based on work by Morrell (1995),^q Smith and Raivo (1995).^r

4.3.1 Tritium

Based on RWMIS data, Atwood and Schlafman^{4,5} listed an activity of only 1.95 Ci of tritium (H-3) in the waste stored in the TSA. Radioactive decay had reduced the activity, recorded in 1977, to 0.7978 Ci by 1993. Examination of the RWMIS entry indicates that the waste containing the H-3 is likely to be ALLW, not TRU waste.

As described below, additional H-3, not reported in RWMIS, is estimated to be in the stored waste.

Two incidents at the Rocky Flats Plant resulted in tritium-contaminated waste being sent to the TSA (INEL 1984).^s Nearly all of the tritium in the stored waste is believed to exist in waste generated during the cleanup and decontamination work stemming from these two incidents.

Information compiled by the INEL^s in 1984 on the tritium-contaminated waste from these incidents was based primarily on operator interviews. That document was used to develop the following inventory of tritium in the waste.

Tritium-bearing waste associated with the first incident was shipped to the TSA in late 1973 and early 1974. The great majority of the tritium is located in a total of 11 drums. Very small amounts of tritium (possibly up to the mCi range) were in drums shipped a few months later.

Of the 11 drums, 9 were shown by assay at Rocky Flats Plant to have at least 1 g Pu and are almost certainly TRU waste, not ALLW. Two drums were shown by assay to have <1 g Pu. These two drums could conceivably be ALLW. (For a 300-lb drum, for example, about 0.17 g of weapons-grade Pu would represent a concentration of 100 nCi TRU/g.) It was assumed that these two drums were ALLW.

In the absence of more definitive information, the distribution of tritium throughout the 11 drums was assumed to be uniform. The activity of tritium in the nine TRU waste drums was thus estimated to be 9/11 of

q. D. K. Morrell, *RWMIS Non-Actinides Summary*, EDF PSPI-015546-07, September 29, 1995.

r. T. H. Smith, B. D. Raivo, *INEL Stored Waste (TSA) Non-database derived, Nonactinide Estimated Activity*, EDF PSPI-015546-08, October 12, 1995.

s. T. L. Clements, Jr., *Tritium-Contaminated Stored TRU Waste*, letter to K. B. McKinley, EG&G Idaho, Inc., TLC-6-84, May 14, 1984.

Table 4-48. Refined activity inventory for select nuclides.^a

Category	Nuclide	Non-RWMIS derived activity decayed to 1993 (Ci)
Contact handled ALLW	H-3	46.9+1.0+3.9 = 51.8
	Co-60	4.6
	C-14	0.034
	Tc-99	0.001
	I-129	3.6E-07
Contact handled TRUW	H-3	211.8
	Co-60	0
	C-14	1.9
	Tc-99	0.030
	I-129	1.1E-05
Remote handled ALLW	H-3	0
	Co-60	0
	C-14	0
	Tc-99	4.0E-03
	I-129	1.4E-06
Remote handled TRUW	H-3	0
	Co-60	0
	C-14	0.45
	Tc-99	0.50
	I-129	1.7E-04
Total ALLW and TRUW	H-3	263.6
	Co-60	4.6
	C-14	2.384
	Tc-99	0.535
	I-129	1.828E-04

a. EDF PSPI-015546-08, 10/12/95.

the total of approximately 600-800 Ci for the 11 drums, or 491-655 Ci. The conservative value assumed was 655 Ci as of late 1973. The activity of tritium in the two ALLW drums was estimated to be 2/11 of the total, or 109-145 Ci. The conservative value assumed was 145 Ci as of late 1973.

The waste forms resulting from the first incident are primarily wet combustibles, dry combustibles, and leaded rubber gloves.

Tritium-bearing waste associated with the second incident is located in two drums shipped in 1981. No information is available on whether these drums are likely to be TRU waste or ALLW. It was assumed that both drums were ALLW. The amount of tritium in each of these drums was estimated to be 1 Ci, for a total of 2 Ci. The waste is in the form of dry combustibles.

Because of the absence of remote-handled (RH) drums in the stored waste from RFP, it was assumed that all of the tritium-containing drums are contact-handled (CH) waste.

Based on the above information, the total activity of tritium in the TRU waste and ALLW was assumed conservatively to be as follows:

- CH TRU waste 655 Ci as of late 1973 (211.8 Ci decayed to 1993).
- RH TRU waste 0
- CH ALLW 145 + 2 = 147 Ci at the time of generation. Of this activity, 145 Ci was generated in late 1973 (46.9 Ci decayed to 1993), plus 2 Ci in 1981 (1.0 Ci decayed to 1993), 1.95 Ci recorded in RWMIS in 1977 (0.7978 Ci decayed to 1993).
- RH ALLW 0

The activity decayed to 1993 for tritium as derived from non-database information sources for these two incidents is estimated to be 211.8 Ci + 46.9 Ci + 1.0 Ci = 259.7 Ci (in addition to RWMIS H-3 inventory).

4.3.2 Nonactinides in Radiation Sources

A recent waste management study conducted at the INEL in 1994,⁴ which was based on previous studies performed in 1979 and 1980, provides data that are not in RWMIS on radiation sources in RFP waste received at the RWMC. Separate listings are given for the larger and smaller sources. Some of these sources are in the stored waste, and some are in the buried waste. Of those in the stored waste, some may be in the ALLW and some in the TRU waste.

The data in Table 4-49 on the nonactinides (plus Ra-226) in the radiation sources from RFP were obtained from the above study. All entries with an activity of 0.1 Ci or greater were included.

Waste packages shipped before or during October 1970 are generally considered to have been buried in the SDA rather than stored in the TSA. Therefore, the drums in the first, third, and fourth entries of Table 4-49 were assumed to have been buried and are outside the scope of this study.

The second entry in Table 4-49 is probably ALLW because it appears that only radiation sources, lead, and concrete were placed into this drum. Apparently, these particular sources were placed in a sole-purpose package, rather than being added to existing drums already containing waste.

The only nonactinide listed in RWMIS for stored waste from Rocky Flats Plant is the 1.95 Ci of H-3 discussed in Section 4.3.1. It is associated with waste retrieved from Pits 11 and 12 and placed into storage. Based on Card^{4,6}, that waste was buried in Pits 11 and 12 in 1970. Therefore, the 1.95 Ci of H-3 from RFP that is listed in RWMIS does not include any of the H-3 sources in the fifth through ninth entries listed in Table 4-49.

t. T. L. Clements, Jr., and G. R. Darnell, *Rocky Flats Plant Characterization (1954-1980)*, EG&G Idaho, Inc., EDF RWMC-761, July 1994.

Table 4-49. Nonactinides plus Ra-226 in radiation sources received from the Rocky Flats Plant.^a

Shipping date	Package number	Nonactinide activity	Form	TRU waste?
6-18-70 ^b	Drum 444-679	174 Ci Co-60 214 Ci Cs-137	Lead shielded	Probably not
5-9-73	Drum 68-8	64 Ci Co-60	Lead shielded	Probably not
10-70 ^b	Drum (no number)	0.36 H-3	Unknown	Unknown
10-70 ^b	Drum (no number)	0.1 Ci Ra-226	Unknown	Unknown
1975	Box 1544-85251	5 Ci H-3	Unknown	Unknown
1975	Drum 36-01846	0.25 Ci H-3	Scandium tritide	Unknown
1977	Drum D05548	0.25 Ci H-3	Unknown	Unknown
3-31-77	Drum 742-25064	3.1 Ci H-3	Unknown	Unknown
8-78	Drum 742-25667	1.5 Ci H-3	Scandium tritide	Unknown

a. EDF PSPI-015546-08, 10/12/95.

b. Assumed to be in buried waste, not included in this study.

Thus, all of the entries except the first, third, and fourth are (a) in the stored waste, (b) not included in the RWMIS printouts, and (c) because of the years in which they were shipped, not included in the H-3 discussed in Section 4.3.1.

No information is available to guide the assignment of the drums with radiation sources to TRU waste or to ALLW. It was conservatively assumed that the subject drums are all ALLW; the relative contribution of the radiation sources to the nonactinide inventory would be higher for the ALLW than for the TRU waste.

It was assumed that the H-3 sources are in the CH waste. For the Co-60 source, it was assumed that during treatment, the source will be removed from its lead-shielded CH drum just before treatment and addressed with the RH waste.

Based on the preceding discussion, the inventory was supplemented to include the following activities:

- CH TRU waste 0
- RH TRU waste 0
- CH ALLW 64 Ci Co-60 in 1973 (4.6 Ci decayed to 1993)
 10.1 Ci H-3
 5.25 Ci in 1975 (1.901 Ci decayed to 1993)
 3.35 Ci in 1977 (1.358 Ci decayed to 1993)
 1.5 Ci in 1978 (0.6433 Ci decayed to 1993)
- RH ALLW 0 (NOTE: the 64 Ci Co-60 in the CH ALLW above will become RH ALLW when the waste package is disassembled for treatment).

The total activity decayed to 1993 for non-actinides in radiation sources is estimated to be 4.6 Ci Co-60, and $1.901+1.358+0.6433 = 3.9$ Ci H-3 (in addition to RWMIS inventory).

4.3.3 Presence of Other Radionuclides

The radionuclides C-14, I-129, and Tc-99 are often present in small activities in waste generated as a result of the operation of nuclear reactors. The activities of these radionuclides are difficult to measure; they are often not reported or are underreported in waste shipping records. Activities of $4E-5$ Ci and $1.8E-3$ Ci for C-14 and Tc-99, respectively, were reported in RWMIS for the total of all waste (TRU waste plus ALLW) in the TSA. No I-129 was reported.

The radionuclides C-14, I-129, and Tc-99 are potentially of interest because they are very long-lived and are relatively mobile upon release in groundwater. A conservative estimate of their possible activity in the waste was developed as follows.

The activities of these difficult-to-measure radionuclides are often estimated by comparing them with the activities of radionuclides that are readily measured. The activity of C-14 is compared with that of Co-60; the activities of I-129 and Tc-99 are compared with that of Cs-137. Typical values of these activity ratios, often called scaling factors, have been determined by a study performed for the Electric Power Research Institute (EPRI)^{4,7} by evaluating a large quantity of laboratory data; however, there is considerable scatter in the data for these three particular radionuclides.

This scaling-factor approach has been used to attribute activities of these three radionuclides to some of the waste buried in the RWMC Subsurface Disposal Area.^{4,8} The conservative estimates developed for the stored waste were based on the use of scaling factors taken from that reference.

The scaling factor for C-14 in INEL buried waste typically ranges from about $1E-3$ to $1E-2$, depending on the nature of the waste. If one conservatively multiplies the largest of these values, $1E-2$, by the estimated total activity of Co-60, the results in Table 4-50 are obtained.

The scaling factor for Tc-99 in INEL buried waste typically ranges from about $1E-5$ to $2E-4$, depending on the nature of the waste. If one conservatively multiplies the largest of these values, $2E-4$, by the estimated total activity of Cs-137, the results in Table 4-50 are obtained.

The scaling factor for I-129 in INEL buried waste typically ranges from about $3E-8$ to $7E-8$, depending on the nature of the waste. If one conservatively multiplies the largest of these values, $7E-8$, by the estimated total activity of Cs-137, the results in Table 4-50 are obtained.

Because the half-lives of C-14, Tc-99, and I-129 are $5.73E3$, $2.13E5$, and $1.57E7$ years, respectively, the specific years for which the activities are attributed do not affect the future activities to any substantial degree.

Table 4-50. Estimated activities of C-14, Tc-99, and I-129 in stored waste.^a

Difficult-to-measure radionuclide	C-14	Tc-99	I-129
Scaling factor	1E-2 x Co-60	2E-4 x Cs-137	7E-8 x Cs-137
CH TRU waste			
Activity of scaling radionuclide ^b (Ci)	190.37	151.42	151.42
Activity of radionuclide (Ci)	1.9	0.030	1.1E-5
RH TRU waste			
Activity of scaling radionuclide ^b (Ci)	44.64	2491.11	2491.11
Activity of radionuclide (Ci)	0.45	0.50	1.7E-4
CH ALLW			
Activity of scaling radionuclide ^b (Ci)	3.38	5.12	5.12
Activity of radionuclide (Ci)	0.034	1.0E-03	3.6E-07
RH ALLW			
Activity of scaling radionuclide ^b (Ci)	0	19.91	19.91
Activity of radionuclide (Ci)	0	4.0E-3	1.4E-6

a. EDF PSPI-015546-08, 10/12/95.

b. Scaling radionuclides are Co-60 for C-14, Cs-137 for Tc-99, and Cs-137 for I-129. Activities of scaling radionuclides were taken from LITCO August 1995 RWMIS analysis, with the assumptions that (a) MAP entries are 100% Co-60, (b) MFP and unidentified beta-gamma-emitter entries are 50% Cs-137 and 50% Sr-90.

4.4 References

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- 4-2. E. Browne and R. B. Firestone, *Table of Radioactive Isotopes*, John Wiley & Sons, 1986.
- 4-3. I. R. Terry, "A Practical Algorithm to Derive the (α , n) Source Term in a Composite Mixture Containing Actinides," *Nuclear Science Engineering* 113, p. 282, 1993.
- 4-4. M. E. Anderson and J. F. Lemming, *Selected Measurement Data for Plutonium and Uranium*, Mound Laboratory report MLM-3009/ISPO-157, November 1982.
- 4-5. C. L. Atwood and M. J. Schlafman, *Empirical Distributions of Radionuclides from RWMIS Data*, EG&G Idaho, Inc., EGG-RAAM-10741, April 1993.
- 4-6. D. H. Card, *History of Buried Transuranic Waste at INEL*, EG&G Idaho, Inc., WMP 77-3, March 1977.
- 4-7. EPRI, *Updated Scaling Factors in Low-Level Radwaste*, EPRI NP-5077, Impell Corporation, March 1987.
- 4-8. LITCO (Lockheed Idaho Technologies Company), *A Comprehensive Inventory of Radiological and Nonradiological Contaminants in Waste Buried in the Subsurface Disposal Area of the INEL RWMC During the Years 1984-2003*, INEL-95/0135, revision 1, 3 volumes, August, 1995.

