APPENDIX A. RADIOACTIVE WASTE SOURCE TERMS AND CHARACTERISTICS

A.1 DISCUSSION

In this report, a number of engineering estimates, assumptions, and ground rules are used to determine radioactive waste projections through the year 2030. Many of these involve parameters that characterize certain types of waste (e.g., see Table A.1). In other instances, estimates were made of the waste volume generated per unit of product throughput for each step in the fuel cycle. This appendix is a compilation of source terms and characteristics used for making radioactive waste projections. Source terms are used to describe quantitative and qualitative characteristics of radioactive wastes. As used in this report, the source term for a particular waste is comprised of two components unique to that waste: (1) the number of curies of radioactivity expressed either per unit of facility production or per unit of waste volume or mass and (2) a listing of the relative radioactivity contributions of component radioisotopes.

The source terms used in the analysis of this report are based on reported historical data, engineering estimates, calculations, and/or experimental data. Documentation of the source terms and key waste-modeling parameters is provided in the following sets of figures and tables (based primarily on refs. 1 through 5). Detailed information on how these source terms and modeling parameters were derived is available, mainly in ref. 1 and its update (ref. 2).

Representative DOE LLW radionuclide compositions are described in Table A.2 (based on ref. 1). Average concentrations for representative radionuclides in LLW disposed of at commercial sites are given in Table A.3. This information was adapted from ref. 3. Table A.4 gives a summary of major sources and estimated characteristics of commercial greater-than-Class-C LLW (data from refs. 4 and 5).

The characteristics of many types of naturally occurring radioactive materials are based on the properties of the radionuclides from the natural decay series of ^{232}Th, ^{235}U, and ^{238}U. Major characteristics of the radionuclides that comprise each of these three natural decay chains are given in Table A.5 (adapted from refs. 6 and 7).

A.2 SPECIAL-CASE WASTE

Special-case waste (SCW) is radioactive waste that is generated from DOE-sponsored activities that has limited or no planned disposal alternatives because it does not fit into the typical management plans developed for the major radioactive waste types. As defined by DOE, SCW is not HLW or TRUW, but is waste that requires greater confinement than shallow-land burial.[8] Except for indefinite storage, no management strategy for SCW currently exists. SCW has been generated over the history of DOE missions and reflects a wide spectrum of radiological characteristics. The following categories of materials have been identified as SCWs:

- excess nuclear material,
- “failed” spent nuclear fuel debris,
- materials requiring special PA [also called special performance assessment required (SPAR) wastes],
- sealed source(s) awaiting a disposal option, and
- uncharacterized waste.

A summary of current (FY 1997) SCW inventories is provided in Table A.6 (data from ref. 9).

A.3 REFERENCES

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Table A.1. Estimated representative unit activity and thermal power characteristics of various types of radioactive materials and wastes

Radioactive material or waste type	Unit activity (Ci/m^3)	Unit thermal power (W/m^3)
Spent nuclear fuel[a]		
BWR	1,000,000–10,000,000	3,500–40,000
PWR	2,000,000–20,000,000	7,500–65,000
High-level waste (untreated)	1,500–15,000	5–50
Transuranic waste		
Remote-handled, stored	1,000	1–2
Contact-handled, stored	25–50	0.5–1.5
Buried	0.25–0.50	0.005–0.010
Low-level waste[b]		
DOE sites	9–27	0.012–0.054
Commercial sites[c]	4.6–6.4	0.30–1.60
Class A	0.5–0.7	0.03–0.10
Class B	55–60	14–15
Class C	0.1–>7,000[d]	0.003–115[d]
GTCC[e]	>0.1–No limit	>0.003–No limit
Uranium mill tailings	0.010	0.00020

[a]Lower-bound levels are based on cumulative spent nuclear fuel discharged; upper-bound levels are based on annual discharges.

[b]Based on 1986–1988 Solid Waste Information Management System (SWIMS) and the National Low-Level Waste Management Program (LLWMP) data access system, both of which were maintained by EG&G, Idaho, Inc., Idaho Falls, Idaho.

[c]Waste classification is defined by the NRC in 10 CFR Part 61.55 on the basis of concentration of certain long- and short-lived radionuclides. The classification system is designed to minimize potential exposures in both the short and long term. The gross Ci/m^3 shown above are representative of typical LLW shipped to commercial disposal sites. Nuclear power plant wastes account for most of the radioactivity (~96%) and include Class A, B, and C. Essentially all medical wastes are Class A. Industrial wastes are largely Class A, but they contain some Class B and C.

[d]Maximum for ^{63}Ni in activated metal or ^{90}Sr. There is no limit on concentration of ^{3}H, ^{60}Co, or nuclides with half-lives <5 years. The maximum thermal power shown is based on the highest reported gross Ci/m^3 analysis for irradiated core components (1986–1988) and assumes all the activity is due to ^{60}Co, which would yield the greatest heat output. If the activity is due to activation products, such as ^{54}Mn, ^{58}Co, etc., the Ci/m^3 could be much higher for individual shipments, and the total W/m^3 could exceed the value shown.

[e]In temporary storage. The concentration of actinides and ^{129}I determines the lower activity boundary. There is no limit on concentrations of ^{3}H, ^{60}Co, or nuclides with half-lives <5 years.

Table A.2. Representative DOE LLW radionuclide composition by percent activity[a]

Uranium/thorium		Fission product		Induced activity		Alpha, <100 nCi/g		Other	
Nuclide	Composition	Nuclide	Composition	Nuclide	Composition	Nuclide	Composition	Nuclide	Composition
^{208}Tl	0.0017	^{60}Co	0.08	^{51}Cr	4.95	^{238}Pu	2.62	^{3}H	1.22
^{212}Pb	0.0045	^{90}Sr	7.77	^{54}Mn	38.10	^{239}Pu	0.20	^{14}C	0.06
^{212}Bi	0.0045	^{90}Y	7.77	^{58}Co	55.40	^{240}Pu	0.70	^{54}Mn	6.76
^{212}Po	0.0029	^{95}Zr	1.27	^{59}Fe	0.49	^{241}Pu	96.4	^{58}Co	6.24
^{216}Po	0.0045	^{95}Nb	2.83	^{60}Co	0.87	^{241}Am	0.004	^{60}Co	18.03
^{224}Ra	0.0045	^{99}Tc	0.02	^{65}Zn	0.19	^{242}Cm	0.056	^{90}Sr	8.48
^{228}Ra	0.0269	^{125}Sb	2.93			^{244}Cm	0.020	^{90}Y	8.48
^{228}Ac	0.0269	^{125m}Te	0.73					^{99}Tc	0.12
^{228}Th	0.0045	^{106}Ru	6.39					^{134}Cs	13.98
^{231}Th	0.0259	^{106}Rh	6.39					^{137}Cs	18.45
^{232}Th	0.273	^{134}Cs	0.38					^{137m}Ba	17.45
^{234}Th	33.197	^{137}Cs	17.31					^{238}U	0.73
^{234m}Pa	33.197	^{137m}Ba	16.38						
^{234}Pa	0.0034	^{144}Ce	14.67						
^{235}U	0.0258	^{144}Pr	14.67						
^{238}U	33.197	^{147}Pm	0.06						
		^{151}Sm	0.11						
		^{152}Eu	0.09						
		^{154}Eu	0.09						
		^{155}Eu	0.06						
Total	100.0000		100.00		100.00		100.00		100.00

[a]Based on ref. 1.

Table A.3. Average concentrations for representative radionuclides in LLW at commercial disposal sites[a]

Radionuclide	Half-life[b]	Concentration (Ci/m^3)	Radionuclide	Half-life[b]	Concentration (Ci/m^3)
^{3}H	1.228E+01 y	1.083E+00	^{129}I	1.570E+07 y	2.101E−05
^{14}C	5.730E+03 y	5.079E−03	^{131}I	8.040E+00 d	5.299E−03
^{26}Al	7.300E+05 y	2.980E−10	^{134}Cs	2.062E+00 y	8.661E−02
^{32}Si	1.000E+02 y	3.725E−11	^{135}Cs	3.000E+06 y	1.105E−05
^{32}P	1.428E+01 d	9.292E−04	^{137}Cs	3.017E+01 y	2.431E−01
^{35}S	8.751E+01 d	2.208E−03	^{137m}Ba	2.552E+00 min	2.300E−01
^{36}Cl	3.010E+05 y	6.143E−06	^{141}Ce	3.250E+01 d	1.649E−03
^{40}K	1.280E+09 y	1.766E−07	^{144}Ce	2.849E+02 d	1.463E−02
^{51}Cr	2.770E+01 d	7.137E−02	^{144}Pr	1.728E+01 min	1.463E−02
^{54}Mn	3.122E+02 d	3.895E−01	^{144}Nd	2.100E+15 y	1.689E−10
^{55}Fe	2.730E+00 y	3.112E+00	^{147}Pm	2.623E+00 y	1.317E−02
^{59}Fe	4.445E+01 d	5.081E−03	^{157}Tb	1.100E+02 y	1.012E−10
^{58}Co	7.092E+01 d	2.047E−01	^{158}Tb	1.800E+02 y	3.768E−10
^{60}Co	5.271E+00 y	2.242E+00	^{175}Hf	7.000E+01 d	1.427E−03
^{59}Ni	7.500E+04 y	1.364E−03	^{181}Hf	4.240E+01 d	3.235E−03
^{63}Ni	1.001E+02 y	2.692E−01	^{187}Re	4.100E+10 y	1.772E−11
^{65}Zn	2.441E+02 d	1.174E−01	^{209}Po	3.253E+00 h	1.284E−10
^{85}Kr	1.072E+01 y	8.147E−04	^{226}Ra	1.600E+03 y	2.852E−04
^{89}Sr	5.055E+01 d	6.032E−03	^{229}Th	7.340E+03 y	1.310E−10
^{90}Sr	2.850E+01 y	6.987E−02	^{230}Th	7.540E+04 y	1.721E−08
^{90}Y	2.671E+01 d	6.987E−02	^{232}Th	1.405E+10 y	8.482E−03
^{91}Y	5.851E+01 d	8.859E−03	^{231}Pa	3.276E+04 y	1.016E−10
^{95}Zr	6.402E+01 d	1.036E−02	^{233}U	1.592E+05 y	2.308E−07
^{94}Nb	2.030E+04 y	1.659E−05	^{234}U	2.454E+05 y	5.368E−05
^{95}Nb	3.497E+01 d	1.916E−02	^{235}U	7.037E+08 y	3.179E−05
^{93}Mo	3.500E+03 y	9.273E−12	^{236}U	2.432E+07 y	7.886E−07
^{99}Tc	2.130E+05 y	1.949E−04	^{238}U	4.468E+09 y	9.970E−03
^{103}Ru	3.925E+01 d	5.900E−04	^{237}Np	2.140E+06 y	2.210E−07
^{108m}Ag	1.300E+02 y	5.534E−06	^{239}Pu	2.413E+04 y	1.021E−05[c]
^{110m}Ag	2.498E+02 d	3.600E−02	^{240}Pu	6.563E+03 y	2.504E−06[c]
^{113}Cd	9.000E+15 y	4.223E−12	^{242}Pu	3.763E+05 y	6.148E−07[c]
^{124}Sb	6.020E+00 d	2.621E−03	^{241}Am	4.322E+02 y	4.053E−05
^{125}Sb	2.730E+00 y	1.901E−02	^{243}Am	7.380E+03 y	1.398E−08
^{123}Te	1.300E+13 y	5.710E−07	^{248}Cm	3.400E+05 y	6.220E−07
^{125}I	6.014E+00 d	4.570E−04			
				Total	8.380E+00

[a]Adapted from ref. 3.

[b]y = years; d = days; h = hours; min = minutes; and s = seconds.

[c]Isotopes of plutonium are omitted when this list is applied to waste disposed at Barnwell, South Carolina, because this site has not permitted disposal of plutonium (even though traces of plutonium could have entered with other wastes).

Table A.4. Estimated sources and characteristics of commercial Greater-Than-Class-C LLW[a]

Waste source	Physical form	Primary isotopes of concern for disposal
Utilities		
Reactor operations	Activated metals, instruments, filters, ion-exchange resins, sludges	^{59}Ni, ^{63}Ni, ^{94}Nb, and TRU isotopes
Reactor decommissioning	Activated metals	^{59}Ni, ^{63}Ni, and ^{94}Nb
Fuel testing labs		
Burnup lab operation	Solidified liquids, metal cuttings, glassware, equipment, ion-exchange resins	^{90}Sr and TRU isotopes
Burnup lab decommissioning	Solidified liquids, metals, glassware, equipment	^{90}Sr and TRU isotopes
Sealed sources		
Manufacturer operations	Trash, metal, foils	^{14}C, ^{90}Sr, ^{137}Cs, ^{241}Am, and Pu isotopes
Manufacturer decommissioning	Trash, metal, foils	^{14}C, ^{90}Sr, ^{137}Cs, ^{241}Am, and Pu isotopes
Sources designated as waste	Sealed sources	^{137}Cs, ^{238}Pu, ^{239}Pu, and ^{241}Am
Other		
^{14}C users	Solidified process liquids	^{14}C
Test and research reactors	Activated metals	^{59}Ni, ^{94}Nb, and TRU isotopes
Other	Soil, trash	^{241}Am

[a]Gleaned from information given in refs. 4 and 5.

Table A.5. Major characteristics of the radionuclides that comprise the natural decay series for ^{232}Th, ^{235}U, and ^{238}U[a]

Natural ^{232}Th decay series			Natural ^{235}U decay series			Natural ^{238}U decay series		
Nuclide	Half-life[b]	Principle mode of decay[c]	Nuclide	Half-life[b]	Principle mode of decay[c]	Nuclide	Half-life[b]	Principle mode of decay[c]
^{232}Th	1.4E+10 y	α	^{235}U	7.0E+08 y	α	^{238}U	4.5E+09 y	α
^{228}Ra	5.75 y	β	^{231}Th	1.06 d	β	^{234}Th	24.10 d	β
^{228}Ac	6.13 h	β	^{231}Pa	3.3E+04 y	α	^{234}Pa	1.17 min	β
^{228}Th	1.913 y	α	^{227}Ac	2.2E+01 y	α (1.4 %) β (98.6 %)	^{234}U	2.5E+05 y	α
^{224}Ra	3.66 d	α	^{227}Th	18.7 d	α	^{230}Th	7.5E+04 y	α
^{220}Rn	55.6 s	α	^{223}Fr	21.8 min	β	^{226}Ra	1.6E+03 y	α
^{216}Po	1.5E−02 s	α	^{223}Ra	11.43 d	α	^{222}Rn	3.285 d	α
^{212}Pb	10.64 h	β	^{219}At	56 s	α	^{218}Po	3.1 min	α
^{212}Bi	1.01 h	α (36%) β (64%)	^{219}Rn	3.96 s	α	^{218}At	1.5 s	α
^{212}Po	3.0E−07 s	α	^{215}Bi	7.6 min	β	^{214}Pb	27 min	β
^{208}Tl	3.053 min	β	^{215}Po	1.8E−03 s	α	^{214}Bi	19.9 min	β
^{208}Pb	(stable)	(stable)	^{215}At	1.0E−07 s	α	^{214}Po	1.6E−04 s	α
			^{211}Pb	36.1 min	β	^{210}Tl	1.30 min	β
			^{211}Po	25.2 s	α	^{210}Pb	22.6 y	β
			^{211}Bi	2.14 min	α	^{210}Bi	5.01 d	β
			^{207}Tl	4.77 min	β	^{210}Po	138.4 d	α
			^{207}Pb	(stable)	(stable)	^{206}Hg	8.2 min	β
						^{206}Tl	4.20 min	β
						^{206}Pb	(stable)	(stable)

[a]Adapted from refs. 6 and 7. Other characteristics for these radionuclides are described in Appendix B.

[b]y—years; d–days; h—hours; min—minutes; and s—seconds.

[c]α—alpha decay; β—negative beta decay; EC—electron capture; and IT—isomeric transition (radioactive transition from one nuclear isomer to another of lower energy).

Table A.6. Current volume inventories of DOE site SCW (SPAR)[a]

Site/category	Volume (m^3)	Radioactivity (Ci)	Mass (kg)
Hanford	148.0	9.7×10^7	3.6×10^5
INEEL[b]	55.5	5.4×10^6	1.4×10^5
ORNL			
Activated metal[c]	1,651.6	2.5×10^4	3.9×10^4
Beryllium reflectors	26.4	3.8×10^6	2.0×10^4
Reactor control plates and source materials	184.8	1.0×10^4	4.4×10^4
Solid beta-gamma waste	536.2	d	1.3×10^6
ORNL total	2,399.0	$>3.8 \times 10^6$	1.4×10^6
WVDP	d	d	d
NR Sites[e]	1,017.5	d	2.5×10^6
Grand total	3,620.0	$>8.3 \times 10^8$	3.4×10^7

[a]Based on ref. 9. SPAR = special performance assessment required.

[b]Includes contributions from ANL–W.

[c]Activated metals from four reactors: High Flux Isotope Reactor (HFIR), Oak Ridge Research Reactor (ORRR), Bulk Shielding Reactor (BSR), and Molten Salt Reactor Experiment (MSRE).

[d]Unknown.

[e]DOE Naval Reactors Program (NE-60) sites.