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Relevance of Biotic Pathways to the Long-Term Regulation of Nuclear Waste Disposal

Topical Report on Reference Western Arid Low-Level Sites

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ABSTRACT

The purpose of the work reported here was to develop an order of magnitude estimate for the potential dose to man resulting from biotic transport mechanisms at a reference western arid low-level waste site. A description of the reference site is presented that includes the waste inventories, site characteristics and biological communities. Parameter values for biotic transport processes are based on data reported in current literature. Transport and exposure scenarios are developed for assessing biotic transport during 100 years following site closure. Calculations of radionuclide decay and waste container decomposition are made to estimate the quantities available for biotic transport. Dose to a man occupying the reference site following the 100 years of biotic transport are calculated. These dose estimates are compared to dose estimates for the intruder-agricultural scenario reported in the DEIS for 10 CFR 61 (NRC). Dose to man estimates as a result of biotic transport are estimated to be of the same order of magnitude as the dose resulting from the more commonly evaluated human intrusion scenario. The reported lack of potential importance of biotic transport at low-level waste sites in earlier assessment studies is not confirmed by the findings presented in this report. These results indicate that biotic transport has the potential to influence low-level waste site performance. Through biotic transport, radionuclides may be moved to locations where they can enter exposure pathways to man.

SUMMARY

The development of an order of magnitude assessment of the importance of biotic transport at a reference low-level waste disposal site in the arid west indicates that biotic transport processes are potential contributors to site performance and future dose to man. Calculations indicate that at the reference disposal site, which is similar in physical characteristics to currently operated sites, resulting dose to man is of the same order of magnitude as doses from current human intrusion scenarios. Two conditions were identified as controlling the dose results. First, the surface area contaminated over the burial ground was substantially larger for the biotic transport scenario. Second, the resulting radionuclide mixture at the surface was influenced by the selective long-term accumulation of the more biologically available radionuclides. Several key assumptions are identified. These assumptions require further evaluation for a complete assessment of potential impacts from biotic transport. The role of biotic transport in the operation and regulation of low-level waste management facilities is not yet fully understood.

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1.0 INTRODUCTION

This report is concerned with one aspect of the assessment of potential dose to man from low-level radioactive waste disposal sites. Concern for potential human exposure to radioactivity has resulted in a large number of management policies, regulatory guidelines, environmental assessment tools, and environmental assessments. A previous report was concerned with several of these and concluded that an adequate evaluation of biotic transport has not been published (McKenzie et al. 1982). This report contains an assessment of the potential magnitude contributions from biotic transport would make on radiation dose to man for a reference low-level waste disposal site in the arid West. Biotic transport is defined as the actions of plants or animals that transport radioactive materials from a low-level burial ground to a location where these radionuclides can enter into human exposure pathways such as food chains.

Three biotic transport mechanisms are possible at a waste disposal site. They are: 1) transport enhancement, 2) intrusion and active transport, and 3) secondary transport (McKenzie et al. 1982). In transport enhancement, plants and animals modify the wastes or waste site such that there is an increased potential for radionuclide transport. Burrowing animals and invertebrates, for example, construct tunnels that enhance exchange of gases and infiltration of surface water. Intrusion and active transport occur when biota penetrate the waste zone and cause a horizontal or vertical redistribution of waste material. In secondary transport, radionuclides are available to biota for a horizontal displacement after they have been mobilized by other processes.

In this report, only intrusion and active transport by biota are considered. An initial qualitative assessment indicated that intrusion and active transport is potentially the most important biotic transport mechanism (McKenzie et al. 1982). In addition, little documented information is available for quantifying either transport enhancement or secondary transport mechanisms. Two processes are considered within intrusion and active transport. They are direct intrusion into buried waste by burrowing mammals and invertebrates and penetration by plant roots. These two processes potentially result in transport and redistribution of radionuclides in the low-level waste trench cover and on the trench surface. The resulting soil concentrations of radionuclides can then contribute to the radiation dose to man through a number of exposure pathways. In this report, we are considering the following: direct exposure from contaminated ground, inhalation of resuspended radioactive particles, and ingestion of contaminated food products in the human food chain.

It is likely that site characteristics will influence the magnitude of biotic transport as a result of different biotic communities. In this report, we examine a representative western arid site with associated plant and animal communities. The assessment includes consideration of long-term events such as community succession. Waste inventories and disposal scenarios are examined for both current and future practices, as these will also influence the magnitude of biotic transport.

Section 2 of this report contains a description of the reference western arid disposal site and the surrounding environment. Reference radionuclide inventories called waste spectra are developed for the arid site and are presented in this section. Radiation exposure scenarios are developed for biotic transport and human intrusion via agricultural products in Section 3. Section 4 presents the results from the dose calculations for the cases with and without biotic transport. A discussion of those results and their implications is contained in Section 5. In this section, conclusions are drawn from this assessment concerning the relative importance of biotic transport processes at a western arid site.

1.1 REFERENCES

McKenzie, D. H., L. L. Cadwell, C. E. Cushing, Jr., R. Harty, W. E. Kennedy, Jr., M. A. Simmons, J. K. Soldat, and G. Swartzman. 1982. *Relevance of Biotic Pathways to the Long-Term Regulation of Nuclear Waste Disposal. A Report on Tasks 1 and 2 of Phase 1.* NUREG/CR-2675, PNL-4241, Vol. 1. Nuclear Regulatory Commission, Washington, D.C.

2.0 REFERENCE ARID SITE DESCRIPTIONS

To assist in determining the importance of biotic transport at low-level waste (LLW) burial grounds, we have defined a reference site and waste inventory. The site description is constructed to represent conditions at sites currently operating in the western United States, although not all of the features of the reference arid site are exactly the same as those encountered at currently operating sites. However, the use of representative generic parameters provides a uniform basis for analyzing the relative impacts of biotic transport.

In this section, we review the characteristics of currently operating LLW burial grounds and establish the representative parameters to be used in the analysis that follows in later sections. We also briefly discuss the arid environmental plant and animal components that could contribute to biotic transport. Finally, we develop the waste spectra for both current and future waste forms.

2.1 REFERENCE ARID SITE LOW-LEVEL WASTE BURIAL GROUND

Two commercial low-level waste (LLW) burial grounds are located in the low rainfall areas of the western United States: Beatty, Nevada and Richland, Washington. The physical and operational characteristics of these LLW burial grounds are described and summarized in a recent document by Murphy and Holter (1980, Sec. 3.1.1). These two sites received a variety of LLW originating from nuclear reactor operations, nuclear fuel-cycle facilities, university and industrial research centers, medical diagnostic and treatment facilities, radiopharmaceutical manufacturers, and waste disposal and decontamination companies. The locations for these commercial burial grounds were selected on the basis of regional requirements for radioactive waste disposal and favorable site conditions. The important physical characteristics of the Beatty and Richland sites are summarized in Table 2.1-1. Both sites have similar desert characteristics with a relatively large depth to the saturated ground-water zone.

Radioactive waste disposal operations are generally similar to conventional sanitary landfill operations, with additional care taken in operations concerning the handling of radioactive materials. For the western sites, burial occurs in open, unlined trenches. Each trench contains a mixture of radionuclides and waste forms. A brief summary of the operating practices at the Beatty and Richland LLW burial grounds is given in Table 2.1-2. Overall operations at those two sites are similar. The waste materials and containers are placed unsorted and directly in the open trenches as received. The trenches are then backfilled with excavated earth when filled to waste capacity, or filled as required to provide shielding or security. The uncompacted earthen backfill is built up to form trench caps at both sites (Murphy and Holter 1980, Sec. 3.1).

A generic LLW burial ground is used here to provide a uniform basis for a comparative analysis. Such a burial ground has been defined for an arid

TABLE 2.1-1. Commercial Burial Site Characteristics for Sites in the Western United States[a]

Characteristic	Beatty, Nevada	Richland, Washington
Licensed Area (ha)	32	40
Burial Capacity (m^3)	7.4×10^5	9.1×10^5
Climate	Arid	Semi-Arid
Mean Annual Precipitation (cm)	10	20
Plant Community Composition	Creosote Bush, Annual Forbs	Sagebrush; Cheatgrass Understory
Geomorphology	Basin and Range Desert	Columbia Plateau Semi-Desert
Surface Material	Alluvial Sand and Gravel	Clay, Sand and Gravel
Thickness (m)	200	150
Bedrock Classification	Metamorphic and Sedimentary, Folded	Volcanic Basalt
Depth to Saturated Ground Water (m)	80 - 90	100
Nearest Surface Water	Amargasa River (3 km)	Columbia River (10 km)
River Flow	Ephemeral, Following Storms	Large, Perennial
Water Flow Paths from Burial Areas	Unsaturated Flow in Sand and Gravel Pores	Unsaturated Flow in Sand and Gravel Pores

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(a) Taken in part from Table 3.1-2 of Murphy and Holter (1980), and from Table 24.4 of U.S. Environmental Research and Development Administration (1976).

TABLE 2.1-2. Operating Practices at LLW Burial Grounds in the Western United States[a]

Practice	Beatty, Nevada	Richland, Washington
Burial Trench Size (m)	260 x 12-15 x 8 deep	90 x 8 x 6 deep
Waste Disposal Procedure	Trench Filled to 1m of Surface	Trench Filled to 0.6m of Surface
Waste Covering Frequency	As Trench is Filled	As Trench is Filled
Cover:		
Type	Excavated Earth Fill, No Compacting	Excavated Earth Fill, No Compacting
Depth	1m to 2m Total; Mounded to 0.6m Above Grade	1m to 2m Total; Mounded to 1m Above Grade
Provisions for Water	None	None

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[a] Taken in part from Table 3.1-3, of Murphy and Holter (1980), and from Table 24.1, of U.S. Energy Research and Development Administration (1976).

site in a conceptual decommissioning study by Murphy and Holter (1980, Section 7.0). Some of the features of the reference arid site and facility may not be exactly the same as those encountered at either Beatty or Richland. However, the use of representative parameters will aid in comparing impacts from a biotic transport scenario with those from a human intrusion scenario.

The following key assumptions are made for the reference arid site shallow-land burial facility:

- The reference burial ground operates for 30 years or until all the trenches are full.
- Current practices are assumed in design and operation of trenches.
- All wastes accepted for burial are solids packaged in nonradioactive outer containers. Wastes that contain free liquids are assumed to have been solidified by mixing in cement, urea formaldehyde, or other solidifying agents prior to burial.

- Procedures during burial ground operation are assumed to be such that the ground surface is free of radioactive contamination after the last trench onsite is filled.
- Maintenance of the trench caps is such that erosion is controlled until the site is closed.

The following sections contain discussions of the physical description of the site and waste trenches for the reference burial ground.

2.1.1 Physical Description of the Reference Arid Site

The reference arid site is assumed to be located on an upland area of generally flat terrain (Figure 2.1-1). The near surface soils consist mainly of stream-lined beds of pebble gravel, cobble gravel and boulders in a sandy matrix. Mounds of windblown silt, dune sand, and loess overlay the glacial deposits. A summary of the site characteristics of the reference arid site (taken from Section 7 of Murphy and Holter 1980) is given in Table 2.1-3.

The distance to bedrock is assumed to be in excess of 100m. The water table (top of the saturated zone) is assumed to be about 60 m below the surface. Recharge of the saturated zone occurs through precipitation runoff from the mountain ranges west and southwest of the site.

The climate of the reference western site is mild and dry. Average annual precipitation is about 16 cm, with most of the rainfall occurring in

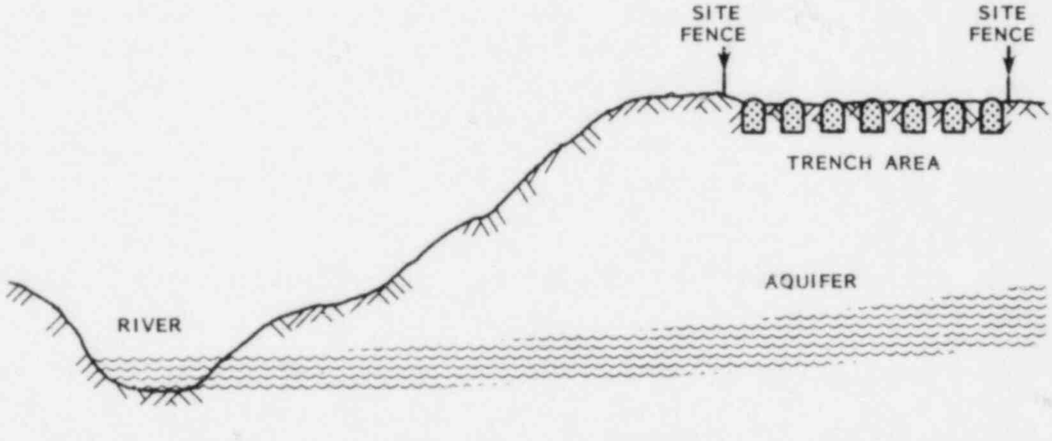

FIGURE 2.1-1. Schematic Cross Section of the Reference Arid LLW Burial Ground

TABLE 2.1-3. Characteristics of the Reference Arid Site LLW Burial Ground[(a)]

Characteristic	Value
Surface material	Silt, Sand, Gravel
Bedrock material	Basalt
Bulk density of surface material	1.7×10^3 kg/m^3
Distance to surface water	16 km
Depth to ground water	60 m
Ground-water gradient	0.18%
Average ground-water velocity	200 m/yr

(a) Taken in part from Table 7.4-1 of Murphy and Holter (1980).

the late fall and early winter. Evaporation and evapotranspiration account for the return to the atmosphere of essentially all of the annual rainfall (Isaacson and Brown 1978).

Mean monthly wind speeds range from about 2 m/s in winter to about 4 m/s in the summer. The prevailing winds are generally from the northwest. Peak gusts exceeding 20 m/s have been observed fairly frequently (Murphy and Holter 1980).

2.1.2 Reference Trench Information

The plot plan for the reference arid burial ground is shown in Figure 2.1-2. Total site area is assumed to be about 70 ha*. The site is assumed to be cleared of existing vegetation prior to the onset of burial operations. The burial trenches occupy about 50 ha. The remaining land is used for buildings, access roads, and the exclusion area around the site. The site perimeter is fenced with a 1.8-m-high chain link fence topped with a three-strand barbed wire outrigger.

The parameters that describe the site capacity for radioactive waste are listed in Table 2.1-4. The total site waste capacity is about $1.5 \times 10^6 m^3$ in 180 burial trenches. Each trench is 150 m long, 15 m wide at the top, sloping to 10 m wide at the bottom, and 7.5 m deep. Figure 2.1-3 shows

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*One ha equals 10,000 m^2 or 2.5 acres.

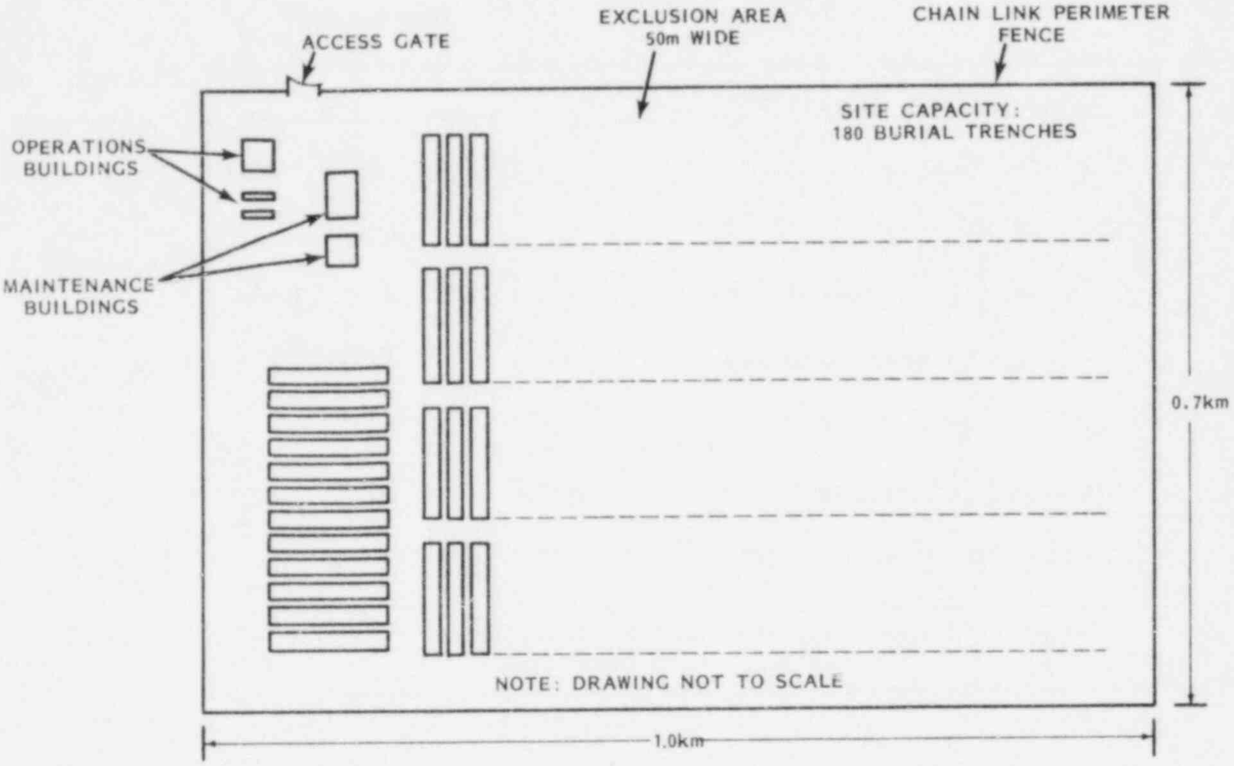

FIGURE 2.1-2. Plot Plan for the Reference Arid Site LLW Burial Ground

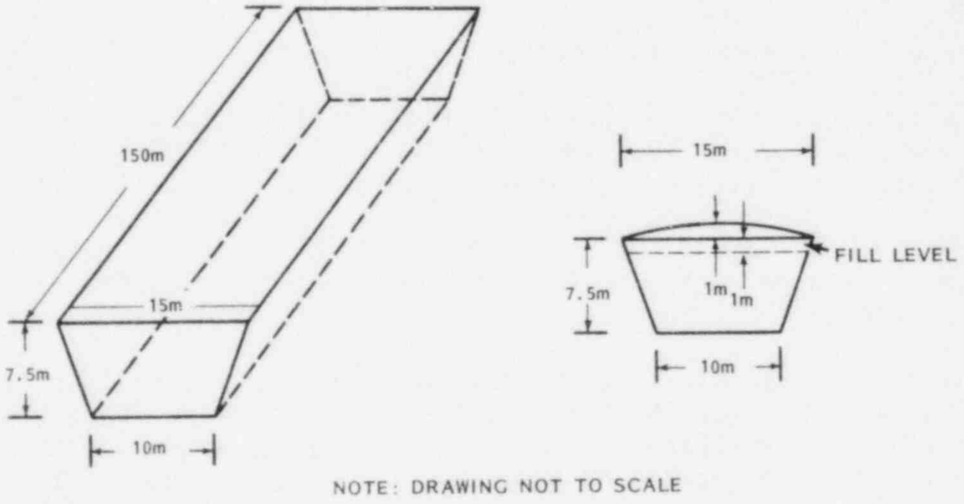

FIGURE 2.1-3. Reference Arid Site LLW Burial Trench

TABLE 2.1-4. Parameters for the Reference Arid Site LLW Burial Ground[a]

Site Parameter	Value
Total area	70 ha
Site waste capacity	1.5×10^6 m^3
Number of burial trenches	180
Burial trench dimensions	150m x 15m x 7.5m
Waste volume per burial trench	14,000 m^3

[a] Taken in part from Table 7.2-1 of Murphy and Holter (1980).

the dimensions and design of a reference trench. A minimum space of 3 m is assumed between the top edges of adjacent trenches.

2.2 REFERENCE ENVIRONMENT

The reference environment assumed for the western site is similar to that for much of the western plains and intermountain valleys. Annual precipitation is generally 20 cm or less; on average, the annual evaporation rate exceeds annual precipitation. Summers are generally warm and dry. Most of the annual precipitation occurs from fall through early spring. Lack of water results in relatively sparse plant and animal communities. The vegetation is composed largely of grasses, forbs and shrubs. Subsequent to disturbance of existing vegetation, annual forbs and grasses dominate early plant successional stages. In time the plant community will be dominated by shrubs and perennial grasses, but that process is gradual and is assumed not to occur for 100 years.

Among the animal community, small to medium-sized mammals and some invertebrates construct burrows and spend part or most of their time below ground. Although some birds and reptiles also use burrows, they are not considered to be responsible for burrow construction. Activity of the biota (animal burrowing and plant rooting depth) is limited to the upper 3 m of soil and most of it occurs within the upper meter.

Parameters used to quantify transport by plants and animals in this evaluation are primarily from the literature and represent what we believe to be realistic for average conditions. In fact, communities experience changes in species composition and density through time and populations are not uniformly distributed. Over several hundred years we expect annual rates of contaminant transport to reflect these changes. The only attempt that we have made to "anticipate" this change is to account for plant succession by restructuring the plant community after 100 years.

2.3 REFERENCE RADIONUCLIDE INVENTORIES FOR THE ARID SITE

Radioactive wastes that are buried at commercial sites contain a wide variety of radionuclides from many sources. In the Draft Environmental Impact Statement (DEIS) in support of 10 CFR 61, the U. S. Nuclear Regulatory Commission (NRC) projected the volumes of LLW from all sources to the year 2000 (U. S. Nuclear Regulatory Commission 1981, Appendix D). In the DEIS, NRC identifies four separate waste groups that include 36 separate waste streams (see Table D.5 of U. S. Nuclear Regulatory Commission 1981), and predicts waste volumes generated by the year 2000 in each region of the United States (see Table D.9 of U. S. Nuclear Regulatory Commission 1981). They estimate that about 6.5 x $10^5 m^3$ of LLW will be generated in the western United States. The radionuclides considered by the NRC in each western waste stream, their half-lives, and their principal means of production are listed in Table 2.3-1.

In the DEIS, the NRC further identified four waste "spectra" that are used to help determine performance of selected waste treatment options. Waste spectrum 1 is based on assumptions that waste volumes are determined by a combination of past or existing waste management practices. Waste spectra 2 through 4 are based on the assumption that increasingly effective waste treatment options are employed. These options include waste compaction, solidification, and evaporation of free liquids. To account for the use of these options, volume reduction and increase factors are identified by NRC for each waste stream considered (U. S. Nuclear Regulatory Commission 1981, Table D.21). In addition, isotopic concentrations corrected for twenty years of radioactive decay are presented for the radionuclide mixtures in each waste stream.

For this study, we are using the decayed isotopic concentrations for the western United States prepared by the NRC with some modifications. We have combined the 36 waste streams identified by the NRC into six composite waste streams. These waste streams have been corrected by the appropriate volume increase and reduction factors for waste spectra 1 and 2. Waste spectrum 1 is intended to be representative of past and current waste management practices. Some of the LLW waste streams are solidified. No volume reduction processes are assumed, and because of void spaces, most containers are structurally unstable. Waste spectrum 2 is intended to represent the use of improved solidification and volume reduction methods. All reactor liquid wastes are evaporated to 50 weight percent solids prior to solidifications. All compactible trash waste streams are assumed to be compacted. The net result of these methods is to increase the concentration of radionuclide in the waste.

TABLE 2.3-1. Radionuclides Considered in Western U.S. LLW Streams[(a)]

Isotope	Half-Life (Years)	Principal Means of Production
H-3	12	Fission; Li-6 (n, α)
C-14	5.7×10^3	N-14 (n, p)
Fe-55	2.7	Fe-54 (n, γ)
Co-60	5.3	Co-59 (n, γ)
Ni-59	7.5×10^4	Ni-58 (n, γ)
Ni-63	100	Ni-62 (n, γ)
Sr-90	29	Fission
Nb-94	2.0×10^4	Nb-93 (n, γ)
Tc-99	2.1×10^5	Fission; Mo-98 (n, γ), Mo-99 (β^-)
I-129	1.6×10^7	Fission
Cs-135	3.0×10^6	Fission; daughter Xe-135
Cs-137	30	Fission
U-235	7.0×10^8	Natural
U-238	4.5×10^9	Natural
Np-237	2.1×10^6	U-238 $(n, 2n)$, U-237 (β^-)
Pu-238	88	Np-237 (n, γ), Np-238 (β^-); daughter Cm-242
Pu-239	2.4×10^4	U-238 (n,γ), U-238 (β^-), Np-239 (β^-)
Pu-240	6.6×10^3	Multiple n-capture
Pu-241	14	Multiple n-capture
Pu-242	3.8×10^5	Multiple n-capture; daughter Am-242
Am-241	430	Daughter Pu-241
Am-243	7.4×10^3	Multiple n-capture
Cm-243	29	Multiple n-capture
Cm-244	18	Multiple n-capture

(a) Taken from Table D.10 of U. S. Nuclear Regulatory Commission (1981).

The six decayed composite waste streams considered in this study are:

- solid reactor wastes
- solidified liquid reactor wastes
- uranium conversion and fuel fabrication waste
- industrial and institutional wastes
- liquid scintillations wastes
- biowastes.

The decayed waste concentrations for waste spectra 1 and 2 are shown by composite waste stream and radionuclide in Tables 2.3-2 and 2.3-3. These tables show average 20-year decayed waste concentrations of 3.5 Ci/m^3 for waste spectrum 1 and 4.2 Ci/m^3 for waste spectrum 2. The radionuclides in these waste spectra are used to develop soil profiles from intrusion and active biotic transport, and to obtain comparative dose values for the intruder-agriculture scenario presented in the DEIS on 10 CFR 61.

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TABLE 2.3-2. Decayed Radionuclide Concentrations for Waste Spectrum 1[(a)]

Radionuclide	Solid Reactor Wastes (Ci/m^3)	Solidified Reactor Wastes (Ci/m^3)	Uranium Wastes (Ci/m^3)	Industrial Wastes (Ci/m^3)	Liquid Scintillation Wastes (Ci/m^3)	Biowastes (Ci/m^3)	Total for Waste Spectrum 1 (Ci/m^3)
H-3	1.4E-02[(b)]	5.1E-04		1.2E-02	1.1E-02	2.2E-03	4.0E-02
C-14	1.1E-03	3.0E-05		1.1E-03	9.3E-04	1.9E-04	4.0E-03
Fe-55	5.0E-01	5.6E-03					5.0E-01
Ni-59	1.7E-03	1.9E-05					1.7E-03
Co-60	1.3E+00	1.5E-02		1.6E-04	1.5E-03	3.2E-04	1.4E+00
Ni-63	1.4E-01	1.7E-03					1.4E-01
Nb-94	5.4E-05	6.0E-07					5.4E-05
Sr-90	2.8E-03	5.7E-05		3.6E-04	7.9E-04	1.3E-04	4.1E-03
Tc-99	6.3E-05	6.4E-07		7.1E-10	1.1E-09	1.2E-10	6.4E-05
I-129	1.7E-04	1.8E-06					1.7E-04
Cs-135	6.3E-05	6.4E-07					6.4E-05
Cs-137	1.4E+00	1.5E-02		7.9E-04	1.3E-03	1.4E-04	1.4E+00
U-235	4.8E-07	1.7E-08	2.8E-05				2.9E-05
U-238	3.8E-06	1.4E-07	1.8E-04				2.9E-05
Np-237	9.3E-11	3.3E-12					9.6E-11
Pu-238	4.7E-04	4.3E-05					5.2E-04
Pu-239/240	4.2E-04	2.3E-05					4.4E-04
Pu-241	1.4E-02	7.8E-04					1.4E-02
Pu-242	9.2E-07	5.0E-08					9.7E-07
Am-241	3.6E-04	2.7E-05		8.1E-07			3.8E-04
Am-243	2.1E-05	1.8E-06					2.3E-05
Cm-243	3.8E-07	4.2E-08					4.2E-07
Cm-244	2.4E-04	3.1E-05					2.7E-04
Totals	3.4E+00	3.8E-02	2.1E-04	1.4E-02	1.5E-02	3.0E-03	3.5E+00

[(a)] Based on information in Appendix D of (U. S. Nuclear Regulatory Commission 1981).

[(b)] Where 1.4E-02 = 1.4×10^{-2}.

TABLE 2.3-3. Decayed Radionuclide Concentrations for Waste Spectrum 2[a]

Radionuclide	Solid Reactor Wastes (Ci/m^3)	Solidified Reactor Wastes (Ci/m^3)	Uranium Wastes (Ci/m^3)	Industrial Wastes (Ci/m^3)	Liquid Scintillation Wastes (Ci/m^3)	Biowastes (Ci/m^3)	Total for Waste Spectrum 2 (Ci/m^3)
H-3	1.7E-02[b]	1.9E-03		3.6E-02	5.3E-03	2.2E-03	6.2E-02
C-14	1.4E-03	1.1E-04		3.2E-03	4.7E-04	1.9E-04	5.3E-03
Fe-55	6.0E-01	2.0E-02					6.2E-01
Ni-59	2.0E-03	7.0E-05					2.1E-03
Co-60	1.6E+00	5.4E-02		4.9E-04	7.4E-04	3.2E-04	1.7E+00
Ni-63	1.7E-01	6.3E-03					1.7E-01
Nb-94	6.4E-05	2.2E-06					6.7E-05
Sr-90	3.3E-03	2.1E-04		1.1E-03	3.9E-04	1.3E-04	5.2E-03
Tc-99	7.6E-05	2.4E-06		3.1E-09	5.7E-10	1.2E-10	7.8E-05
I-129	2.0E-04	6.5E-06					2.1E-04
Cs-135	7.6E-05	2.4E-06					7.8E-05
Cs-137	1.7E-00	5.3E-02		2.4E-03	6.4E-04	1.4E-04	1.8E+00
U-235	5.8E-07	6.3E-08	8.6E-05				8.7E-05
U-238	4.6E-06	5.0E-07	5.3E-04				5.4E-04
Np-237	1.1E-10	1.2E-11					1.2E-10
Pu-238	5.7E-04	1.6E-05					5.8E-04
Pu-239/240	5.0E-04	8.4E-05					5.9E-04
Pu-241	1.6E-02	2.8E-03					1.9E-02
Pu-242	1.1E-06	1.8E-07					1.3E-06
Am-241	4.3E-04	9.8E-05		2.4E-06			5.3E-04
Am-243	2.6E-05	6.6E-06					3.2E-05
Cm-243	4.6E-07	1.5E-07					6.1E-07
Cm-244	2.8E-04	1.1E-04					3.8E-04
Totals	4.1E+00	1.4E-01	6.2E-04	4.3E-02	7.5E-03	3.0E-03	4.2E+00

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[a] Based on information in Appendix D of (U. S. Nuclear Regulatory Commission 1981).

[b] Where 1.7E-02 = 1.7×10^{-2}.

3.0 SCENARIO AND SOURCE TERM DEVELOPMENT

To permit a comparative evaluation of the long-term impacts of biotic transport processes at the reference arid site, radiation exposure scenarios and the resulting source terms are required. The source terms, in the form of surface or near-surface radionuclide concentrations in the trench cover soil, are then used to calculate radiation doses to the maximum-exposed individual for human intrusion and biotic transport scenarios. The calculations are based on the radionuclide mixtures defined for waste spectra 1 and 2, discussed in Section 2.3. The following sections contain a discussion of the radiation exposure scenarios and the resulting source terms used in the comparative evaluation.

3.1 10 CFR PART 61 DRAFT ENVIRONMENTAL IMPACT STATEMENT: RADIATION EXPOSURE SCENARIOS

In the DEIS in support of 10 CFR Part 61, the U.S. Nuclear Regulatory Commission (NRC) identified four radiation exposure scenarios for human intrusion (1981, App. H, p. H-15). These scenarios are:

- Intruder-Construction Scenario. An individual excavates at an abandoned disposal site to build a house.
- Intruder-Discovery Scenario. This scenario is a subset of the intruder-construction scenario and also involves excavation into a closed site. The time over which the excavation proceeds is reduced compared to the intruder-construction scenario.
- Intruder-Agriculture Scenario. An individual lives in a house built on a closed disposal site surrounded by contaminated soil resulting from the intruder-construction scenario. The individual consumes vegetables grown in the contaminated soil.
- Intruder-Well Scenario. An individual uses contaminated water from an onsite well.

For this study, we will use the intruder-agriculture scenario for comparison with the biotic transport scenarios. The intruder-agriculture scenario relies on the surface soil concentration developed for the intruder-construction scenario. After loss of institutional controls at the closed burial ground, an intruder is assumed to construct a house over a closed trench. Basement construction is assumed to involve digging a foundation hole 3 m deep. The area of the hole is assumed to be 200 m^2 (20 m by 10 m) at the bottom, and 320 m^2 (26 m by 16 m) at the top. Construction of the basement results in the movement of 232 m^3 of buried waste and 680 m^3 of cover material (U. S. Nuclear Regulatory Commission 1981, App. G, p. G-57 through G-65). This material is assumed to be distributed around the house within a 25 m radius. The resulting area for dilution of the waste, correcting for the area of the house, is about 1800 m^2. If 150 m^3 of waste are mixed in a total of 600 m^3 of soil, the resulting soil concentration is 0.25 times the waste concentration.

To account for the integrity of different waste containers and waste forms in the burial trench, a waste availability relationship is assumed. In this relationship, the fraction of buried waste available for movement is defined by Equation 3.1 as:

$$Q_A(t) = 1 - e^{-\lambda_A t} \tag{3.1}$$

where: $Q_A(t)$ = the fraction of waste available for movement from decomposed containers or waste forms, unitless,

λ_A = the container decomposition constant defined for the waste spectra, yr^{-1}, and

t = the time since burial, in yr.

Container decomposition is assumed to be a function of the time it takes for the containers to decompose:

$$\lambda_A = \ln 2/t_{A_{1/2}} \tag{3.2}$$

where λ_A is defined for Equation 3.1 and where:

$t_{A_{1/2}}$ = the half-time for container decomposition, yr.

It is currently difficult to make an accurate statement about the durability of buried waste containers. Rough estimates of the durability of waste containers buried at arid western sites can be made by reviewing information from the literature. Waste retrieval programs were initiated at the Idaho National Engineering Laboratory (INEL) to develop technology and define costs of exhuming and relocating buried transuranic wastes. The Early Waste Retrieval Project (Card 1977; McKinley and McKinney 1978) was initiated in 1976 to investigate problems associated with retrieval and repackaging of drummed and boxed transuranic waste material that was buried between 1960 and 1963. Retrieval began during 1976. The waste materials and drums were found to be randomly distributed in the trenches. Virtually all of the waste drums were severely rusted and most boxes had deteriorated. Many of the drums were in a fragile state, and some drums containing liquids leaked during exhumation.

For this study, two container decomposition half-times are assumed. Waste spectrum 1 is designed to represent current and past LLW disposal conditions, with waste assumed to resemble that exhumed in the INEL retrieval program. The containers and wastes are assumed to decompose with a 35-year half-time. Waste spectrum 2 is designed to represent a future waste stream, with the increased use of volume reduction and solidification methods. These wastes are assumed to be more durable than past wastes, and are assigned a 70-year half-time.

The surface soil concentrations resulting for waste spectra 1 and 2 after loss of institutional controls, accounting for 120 years of radioactive decay without biotic transport, are shown in Table 3.1-1. Again, these source terms are developed for the intruder-agriculture scenario with corrections made for the specific activity and container decomposition half-time for each waste spectrum.

The maximum-exposed individual residing on this site could be exposed by inhalation of resuspended radionuclides, ingestion of garden crops grown in the soil, and direct exposure to penetrating radiation. To account for the small surface area contaminated by the intruder-agriculture scenario, the individual is assumed to inhale dust with a concentration of 2×10^{-6} g/m^3 for 8 hours per day, 5 days per week or 2000 h/yr. The individual is also assumed to ingest 60 kg/yr of vegetables grown in the contaminated soil, and he is exposed for 2000 hours per year to penetrating radiation from the contaminated surface soil. These parameters and exposure conditions are used in radiation dose calculations, and the resulting doses are compared with doses resulting from biotic transport processes in Section 4.0.

3.2 BIOTIC TRANSPORT SCENARIOS

Active biotic transport processes, including both burrowing activity of mammals and invertebrates into the wastes and uptake of contaminants by natural invading (or established) vegetation, is assumed to occur for 100 years following site closure and prior to the occurrence of the agricultural intruder. The burrowing activity of animals results in excavation of soil, all of which is assumed to be deposited on the surface of the burial ground. Wastes, adjusted for the quantity available (i.e., allowing for waste package decomposition and radioactive decay; see Section 3.1), are assumed to be moved to the surface by burrowing activities in direct proportion to the volume of soil moved from the depths at which animals encounter wastes.

Plants redistribute radionuclides from the buried wastes by uptake through the root system and assumed subsequent uniform distribution of contaminants throughout the plant. The quantity of radionuclides moved by plants is assumed to be in direct proportion to the fraction of root biomass that penetrates the waste storage zone. It is assumed that above-ground plant materials contribute a quantity of radionuclides to the soil on the surface of the burial site equal to the amount contained in the annual biomass produced. Plant roots are assumed to distribute their contaminant

TABLE 3.1-1. Surface Soil Radionuclide Concentrations Resulting from the Intruder-Agriculture Scenario at the Reference Arid Site[a]

Radionuclide	Waste Spectrum 1[b] (pCi/m^2)	Waste Spectrum 2[b] (pCi/m^2)
H-3	1.1E+07	8.4E+06
C-14	2.8E+08	2.0E+08
Fe-55	2.6E-01	1.9E-01
Co-60	1.9E+05	1.4E+05
Ni-59	1.2E+08	8.8E+07
Ni-63	4.9E+09	3.6E+09
Sr-90	2.6E+07	1.9E+07
Y-90	2.6E+07	1.9E+07
Tc-99	4.6E+06	3.3E+06
I-129	1.2E+07	8.8E+06
Cs-135	4.6E+06	3.3E+06
Cs-137	1.0E+10	7.3E+09
Ba-137m	9.5E+09	6.9E+09
U-235	2.0E+06	1.5E+06
Th-231	2.0E+06	1.5E+06
Pa-231	4.5E+03	3.2E+03
Ac-227	3.1E+03	2.2E+03
Th-227	3.1E+03	2.2E+03
Fr-223	4.2E+01	3.1E+01
Ra-223	3.1E+03	2.3E+03
Np-237	6.9E+00	5.0E+00
Pa-233	6.9E+00	5.0E+00
U-233	2.0E+06	1.5E+06
Th-229	1.4E-05	1.2E-05
U-238	2.0E+06	1.5E+06
Th-234	2.0E+06	1.5E+06
Pa-234	2.0E+06	1.5E+06
Pu-242	6.9E+04	5.1E+04
Pu-238	1.7E+07	1.2E+07
Cm-244	4.2E+05	3.1E+05
Pu-240	1.5E+07	1.1E+07
Cm-243	2.7E+03	1.9E+03
Am-243	1.7E+06	1.2E+06
Np-239	1.7E+06	1.2E+06
Pu-239	1.5E+07	1.1E+07
Pu-241	8.2E+06	6.0E+06
Am-241	5.3E+07	3.8E+07

(a) The calculations are performed for 20-year-old decayed waste after loss of institutional controls 100 years later, for a total of 120 years of radioactive decay.

(b) The decayed waste spectra defined in Section 2.3 are used in the intruder-agriculture scenario. The resulting surface concentrations, in pCi/m^2, are assumed to be mixed in the top 0.5 m.

burdens at various depths below the surface in proportion to annual root biomass production at those depths.

At year 100, the total accumulation of radionuclides on the soil surface resulting from plant and animal activities is assumed to be mixed in the upper 0.5 m of the entire burial ground. Radionuclides that accumulate in the subsurface profile as a result of plant root redistribution (animals are assumed to bring contaminants to the surface only) are assumed to be uniformly mixed within 0.5-m-thick profiles. All of the above processes contribute redistributed radionuclides to inhalation and external exposure as well as providing a contaminant source for crop plants, forage plants fed to animals, and vegetables consumed directly by man.

The quantitative assumptions used in calculating animal and plant intrusions into buried wastes are described in the following sections.

3.2.1 Animal Intrusions

Potential animal intruders include a number of burrowing species that occur in the arid and semi-arid west. These animals were classified into six groups of animals (shown in Table 3.2-1) composed of from one to several species with generally similar burrowing habits. The groups include: 1) ground squirrels (eight species), 2) pocket mice and kangaroo rats (14 species), 3) pocket gophers (four species), 4) prairie dogs (three species), 5) badger (one species), and 6) harvester ants (three species). Although this is not a comprehensive list of burrowing animals, it does include those species for which published quantitative data are available on animal density, burrow density, or burrow volumes. We believe these six categories are representative of the burrowing activity and volumes of soil likely to be displaced by animals on an arid low-level waste burial site. A list of individual species included in each category is given in Appendix A.

For each category we selected a representative value for animal density and burrow volume. We assumed one animal per burrow (one colony per burrow for ants) and that the entire burrow volume represented soil excavated below ground and moved to the surface. We then calculated an estimated volume of soil brought to the surface (Table 3.2-1). Although below ground redistribution of soil by burrowing animals has been observed (Winsor and Whicker 1980), we found no data for most species to permit estimation of quantities of soil involved. Data on the volume of soil brought to the surface by pocket gophers was based on the measured volumes of surface soil deposited near burrow entrances (see Appendix A).

Since badgers are a predatory species generally preying on fossorial rodents, much of their burrowing activity is done during prey capture in existing prey burrow systems. Therefore, the volume of soil moved to the surface by badgers would be less than actual burrow dimensions. We used a value of 10% of the estimated badger burrow volume as representing new soil brought to the surface by the badger. A low value (10%) was purposely selected because the only data we could find for the number of badger burrows

TABLE 3.2-1. Burrowing Habits of Potential Animal Intruders at the Reference Arid Low-Level Waste Burial Site

Animal	Percent Distribution of Burrow System Belowground Depth Interval (m)					Density (Animals/ha)		Burrow Volume (m^3)		Estimated Volume of Soil Brought to Surface in First Year (m^3/ha)	Proportion of New Burrow Systems/Year
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	>2.0	Range	Average	Range	Average		
Ground Squirrels[a]	50	30	15	5	0	5.7 - 74	25	.008 - .077	0.020	0.500	0.50 - 1
Pocket Mice and Kangaroo Rats[a]	50	40	5	5	0	0.8 - 180	25	.003 - .103	0.014	0.350	0.75 - 1
Pocket Gophers[a]	85	15	0	0	0	2 - 124	--	.510 - 81.518[b]	8.300[b]	8.300	0.75 - 1
Prairie Dogs[a]	20	20	20	20	20	3.5 - 31.9[c]	10[c]	.120 - .356	0.196	1.960	0.02
Badgers	70	15	5	5	5	--	--	--	0.170	0.211[d]	1.00
Ants	70	10	10	5	5	--	50[e]	--	0.002[f]	0.100	0.10

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[a] Represents several species and several sources of information (see Appendix A).

[b] Estimate of volume of soil excavated per hectare.

[c] Represents density in an individual colony.

[d] Estimated 0.17 m^3/burrow (Lindzey 1976) x 124 burrows/ha/yr (Messick and Hornocker 1981) = 21.08 m^3/ha/yr. However, most of the digging is done in existing prey burrows and the burrow density figure was from an area of very high badger density. For our purposes, we used an estimate of 10% new soil excavation and 10% of reported badger density, therefore 21.08 x .01 = .211 m^3/ha/yr.

[e] Colonies per hectare.

[f] Represents average burrow volume per colony.

per hectare was from a region of high badger density (Messick and Hornocker 1981) and badger burrow volumes were based on natal rearing dens (Lindzey 1976), which are likely to be considerably larger than burrows dug while hunting prey.

Burrowing depths for the six categories of animals were based on the sources identified in Appendix A. For some animals, no literature data was available, so the distribution of burrow volume by depth was estimated based on the animal's general burrowing habits.

The percentage of new burrow systems created each year (Table 3.1-1) is based on information obtained from the literature (Appendix A) and general behavioral characteristics of the species considered. For example, badger burrows are constructed primarily while searching for prey; therefore, an equal number of burrows are probably constructed each year, assuming the population densities of badgers and prey remain relatively constant. Prairie dogs, however, construct semi-permanent colonies (towns) which are used year-after-year. New burrow systems are constructed at a fairly low rate (our estimate = 2%; see Table 3.2-1) once the colony is established.

3.2.2 Plant Intrusion

Vegetative cover for the western arid or semi-arid low-level waste disposal site was assumed to consist of two basic plant communities: (1) an "initial" community dominated by annual species, and (2) a "final" community dominated by perennial species. Plant composition and percent vegetative cover for these communities are presented in Table 3.2-2. The time required for successional change from annual (our "initial") to perennial (our "final") communities in shrub-steppe semi-arid western sites has been estimated to require 100 years (Daubenmire 1968). Although succession is a gradual process, we assumed the change in community type to occur at year 100.

Aboveground annual biomass production for the "initial" plant community was estimated to be 250 g/m^2/yr dry weight (Rickard et al. 1976) and for the "final" community to be 100 g/m^2/yr dry weight (Pearson 1965, Rickard et al. 1976). Calculations for belowground annual biomass production were based on published root-to-shoot weight ratios (Pearson 1965, Barbour 1973, Fernandez and Caldwell 1975, Hinds 1975). Since these root-to-shoot weight ratios were highly variable (range 0.37 - 9.0), we chose ratios that we felt represented minimum and maximum values for both our "initial" and "final" plant communities. Ratios of 0.5 (Hinds 1975) and 1.0 (our estimate) were selected for the "initial" plant community and 1.0 (Pearson 1965) and 9.0 (Barbour 1973, Fernandez and Caldwell 1975) for the "final" plant community.

TABLE 3.2-2. Plant Community Composition for the Reference Arid Low-Level Waste Burial Site

	Percent Vegetative Cover					
	Annual Grass	Annual Forb	Perennial Grass	Perennial Forb	Shrub	Total
Initial Plant Community[(a)]						
Percent Cover[(b)]	20.0	13.0	0.1	0.6	5.5	39.2
Relative Percent Cover[(c)]	51.0	33.2	0.3	1.5	14.0	100.0
Final Plant Community[(d)]						
Percent Cover	3.0	1.0	90.0	1.0	18.0	113.0
Relative Percent Cover	2.6	0.9	79.6	0.9	15.9	99.9

(a) Average for ten southcentral Washington (Hanford Site) low-level waste burial grounds (Fitzner et al. 1979, Table 3).

(b) Percent ground area covered.

(c) Percent composition of plant community (by area covered).

(d) Data for Benton County, southcentral Washington (Daubenmire 1970, Table B-1).

It was assumed that any radionuclides translocated to the aboveground plant parts were deposited annually on the soil surface, whereas radionuclides in the belowground plant growth were distributed each year at various depths in proportion to root biomass distribution profiles.

The root biomass distribution profile (Table 3.2-3) for our "initial" community was based on a modified version of Table A.4 (from Mayer et al. 1981) for a Bromus tectorum community. For our "final" community, it was based on a modified version of Table A.1 (from Mayer et al. 1981) for an Artemisia tridentata community. Modifications of the Mayer et al. (1981) data were necessary since they record maximum rooting depths of 80 and 180 cm for the two plant communities (our "initial" and "final" plant communities, respectively). However, data presented in Klepper et al. (1978) and Cline et al. (1980) indicate that some probable residents (Chrysothamnus nauseosus and Salsola kali, respectively) of our plant communities are rooted even deeper than data in Mayer et al. (1981) here indicate (see Appendix A for a summary of rooting depths).

TABLE 3.2-3. Percent Root Biomass Distribution Profile for the Reference Site "Initial" and "Final" Plant Communities

Plant Community Type	Percent Root Distribution by Depth (m)									
	From Mayer et al. (1981)					Our Modification of Mayer et al. (1981)[a]				
	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5
Initial	95	5	0	0	0	80	5	5	5	5
Final	67	17	11	6	0	65	15	10	5	5

(a) Data used in our modeling efforts (see text for explanation).

Conversion from dry to wet weight for annual above and belowground biomass was calculated on the basis of dry weight(15% of wet weight; see Turner and Kramer, 1980). Radionuclide concentration ratios (Table 3.2-4) were then applied to wet weight biomass to calculate radionuclide content of plants penetrating the buried waste. These concentration ratios are the same used in the FOOD computer program for calculating dose to man from agricultural food products (Napier et al. 1980). These values are assumed for native plant species because of a lack of alternative data.

3.2.3 Source Terms

The source terms resulting from intrusion and active biotic transport processes for waste spectra 1 and 2 for the arid site are shown in Table 3.2-5. These concentrations are assumed to gradually accumulate during 100 years of institutional control with no corrective action taken by waste site management. The source terms are corrected for 100 years of radioactive decay. Corrections for the container decomposition half-time, as discussed in Section 3.1, are also applied to each waste spectrum.

The maximum-exposed individual residing on this site could be exposed by inhalation of resuspended radionuclides, ingestion of garden and farm crops grown in the soil, and direct exposure to penetrating radiation. Since the reference arid low-level waste burial ground covers a substantial area (70 ha), the entire individual's diet, including eggs and meat, is assumed to be grown in or on contaminated soil. The individual is assumed to inhale dust with a concentration of 2×10^{-6} g/m^3 for 8 hours a day 5 day a week, or 2000 hours per year. The individual is exposed for 2000 hours per year to penetrating radiation from the contaminated soil. The parameters and exposure conditions are used in the radiation dose calculations described in Section 4.0. The calculated doses from the biotic transport are then compared with the doses resulting from the human intrusion scenario.

TABLE 3.2-4. Plant Concentration Ratios for Radionuclides

Radionuclide	Concentration Ratio	Radionuclide	Concentration Ratio
H-3	0.00E+00	Np-237	0.25E-02
C-14	0.00E+00	Pa-233	0.00E+00
Fe-55	0.40E-03	U-233	0.25E-02
Co-60	0.94E-02	Th-229	0.42E-02
Ni-59	0.19E-01	Ra-225	0.14E-02
Ni-63	0.19E-01	Ac-225	0.25E-02
Sr-90	0.20E+00	U-238	0.25E-02
Y-90	0.25E-02	Th-234	0.42E-02
Nb-94	0.94E-02	Pa-234m	0.25E-02
Mo-99	0.13E+00	Pa-234	0.25E-02
Tc-99m	0.25E+00	Am-242m	0.25E-03
Tc-99	0.25E+00	Am-242	0.25E-03
Te-129m	0.13E+01	Cm-242	0.25E-02
Te-129	0.13E+01	Pu-242	0.25E-03
I-129	0.20E-01	Np-238	0.25E-02
I-135	0.20E-01	Pu-238	0.25E-03
Xe-135m	0.00E+00	Cm-244	0.25E-02
Xe-135	0.00E+00	Pu-244	0.25E-03
Cs-135	0.20E-02	U-240	0.25E-02
Xe-137	0.00E+00	Pu-240	0.25E-03
Cs-137	0.20E-02	Cm-247	0.25E-02
Ba-137m	0.50E-02	Cm-243	0.25E-02
U-235	0.25E-02	Pu-243	0.25E-03
Th-231	0.42E-02	Am-243	0.25E-03
Pa-231	0.25E-02	Np-239	0.25E-02
Ac-227	0.25E-02	Pu-239	0.25E-03
Th-227	0.42E-02	Cm-245	0.25E-02
Fr-223	0.00E+00	Pu-241	0.25E-03
Ra-223	0.14E-02	Am-241	0.25E-03
U-237	0.25E-02		

TABLE 3.2-5. Surface Soil Concentrations Resulting from Intrusion and Active Biotic Transport Processes at the Reference Arid Site(a)

Radionuclide	Waste Spectrum 1(b) (pCi/m^2)	Waste Spectrum 2(b) (pCi/m^2)
H-3	7.0E+4	7.3E+4
C-14	1.4E+6	1.2E+6
Fe-55	1.4E-3	1.1E-3
Co-60	2.9E+3	2.3E+3
Ni-59	3.1E+6	2.6E+6
Ni-63	1.3E+8	9.9E+7
Sr-90	5.7E+6	4.8E+6
Y-90	5.7E+6	4.8E+6
Tc-90	1.3E+6	1.0E+6
I-129	3.2E+5	2.6E+5
Cs-135	3.3E+4	2.6E+4
Cs-137	7.3E+7	6.1E+7
Ba-137m	7.0E+7	5.8E+7
U-235	1.7E+4	3.1E+4
Th-231	1.7E+4	3.1E+4
Pa-231	3.4E+1	6.6E+1
Ac-227	2.4E+1	4.7E+1
Th-227	2.3E+1	4.7E+1
Fr-223	3.3E-3	7.1E+3
Ra-223	2.4E+1	4.6E+1
Np-237	5.3E-2	4.4E-2
Pa-233	5.3E-2	4.4E-2
U-233	2.3E-5	1.9E-5
Th-229	2.1E-9	2.6E-9
U-238	1.7E+4	2.0E+5
Th-234	1.7E+4	2.0E+5
Pa-234m	1.7E+4	2.0E+5
Pa-234	2.1E+1	2.5E+2
Pu-242	3.8E+2	3.2E-2
Pu-238	9.0E+4	6.5E+4
Cm-244	2.1E+1	3.1E+3
Pu-240	8.3E+4	7.4E+4
Cm-243	2.1E+1	1.9E+1
Am-243	8.7E+3	7.8E+3
Np-239	8.7E+3	7.9E+3
Pu-239	8.4E+4	7.4E+4
Pu-241	4.4E+4	3.9E+4
Am-241	2.8E+5	2.4E+5

(a) The calculations are performed for 20-year decayed waste after loss of institutional controls 100 years later, for a total of 120 years of radioactive decay.

(b) The decayed waste spectra defined in Section 2.3 are used in the intrusion/active biotic transport scenario. The resulting concentrations, in pCi/m^2, are assumed to be mixed in the top 0.5 m of soil.

The quantities of radionuclides that accumulate in soil layers above the buried waste by intrusion active processes are illustrated in Figure 3.2-1 for waste spectrum 1. This figure shows the total Ci/ha present at each of the three soil depths over a 200 year time span. The peak surface accumulation of about 2.4 Ci/ha of trench surface occurs after about 90 years. The quantities shown in Figure 3.2-1 are corrected for radioactive decay and daughter ingrowth with an assumed 35-year container decomposition half-time. Figure 3.2-2 shows the total Ci/ha present at three soil depths over a 200 year time period for waste spectrum 2. The peak accumulation at the surface occurs after about 100 years, and has a value of about 2.0 Ci/ha. These concentrations are corrected for radioactive decay and daughter ingrowth with an assumed 70-year container decomposition half-time.

3.2.4 Calculations of Biotic Transport

The BIOPORT computer program calculates BIOlogical transPORT of radionuclides from a waste disposal site. A complete listing of the computer program used to calculate the intrusion and active biotic transport processes is given in Appendix B. Biological components are plant roots, which absorb radionuclides and translocate then to other plant organs (i.e., roots, stems, and leaves) and subsequently back to the soil; and animals, which move soil and accompanying radionuclides from various strata to the surface.

The computer program calculates biological transport for each year of the simulation and for each radionuclide in the waste inventory. For each year the model: 1) simulates decay of the waste inventory and the waste in each stratum, when present; 2) determines the amount (m^3) of soil brought to the surface from the various strata by animal activity; 3) computes, for each radionuclide in each stratum, a new concentration based on soil movement; 4) computes, for each radionuclide in each soil stratum, a new concentration based on plant activity.

Uptake of radionuclides by a plant is determined by the highest concentration encountered by the plant roots, and by the concentration ratio (CR) for each element. The radioactivity of the plant is apportioned among the roots and leaves based on annual biomass production, the root to shoot ratio and the distribution of the roots within each stratum. Annual biomass production is assumed to recycle each year; thus, radioactive material is added to each soil stratum.

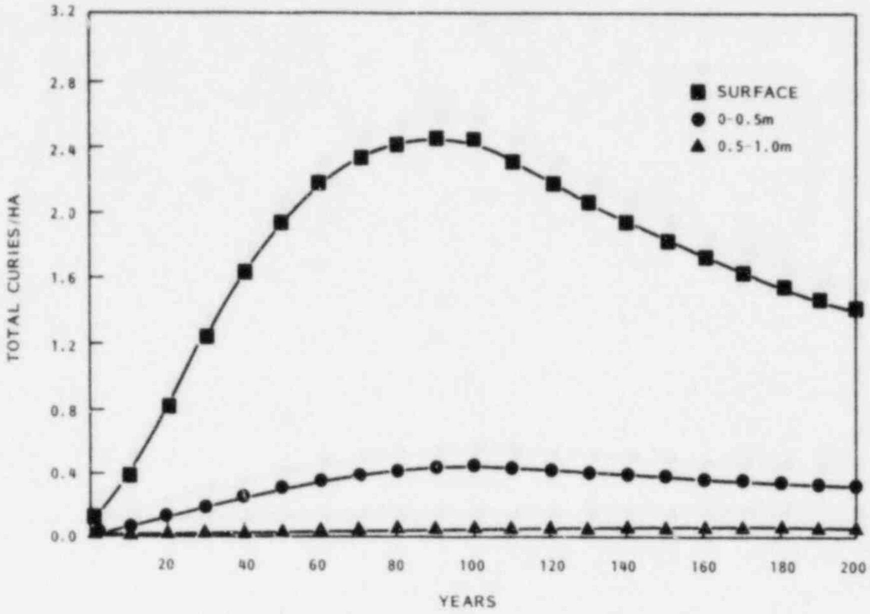

FIGURE 3.2-1. Total Ci/ha Present Over 200 Years, Waste Spectrum 1

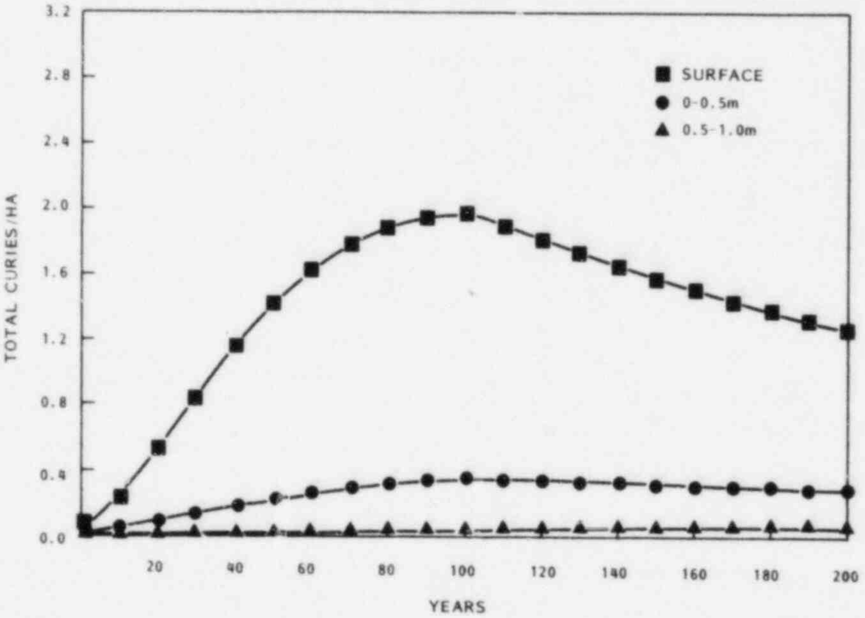

FIGURE 3.2-2. Total Ci/ha Present Over 200 Years, Waste Spectrum 2

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4.0 DOSE CALCULATIONS

Since the mixtures of the radionuclides resulting from the human intrusion scenario and the biotic transport scenario (defined in Section 3) are different, dose calculations are performed to determine the relative impacts of the two scenarios. By using the same environmental pathway and dose analysis model for the source terms defined in Tables 3.1-1 and 3.2-5, a direct comparison of the scenarios can be made. Since the scenarios are considered to be preliminary at this time, the absolute magnitude of the calculated doses are less important than their relative magnitude. This section contains a discussion of the pathway and dose models used, the calculated doses for the human intrusion and the biotic transport scenarios, and a comparison of the critical organ doses from the two scenarios.

4.1 DOSIMETRY MODELS

The PNL computer program MAXI (Napier et al. 1979; Murphy and Holter 1980) is used to calculate the maximum annual dose to an exposed individual from a large number of exposure pathways. This program uses dose factors from the DACRIN (Houston, Strenge, and Watson 1974) computer program for inhalations dose calculations. For ingestion pathways, dose factors from the FOOD and ARRRG (Napier et al. 1980) computer programs are used in MAXI for both terrestrial and aquatic food products.

The general expression for calculating the annual dose to an internal organ during any year after the start of continuous exposure is expressed as:

$$A_t = R_t^\star + \sum_{j=1}^{t-1} \left(R_{j,(t-j+1)} - R_{j,(t-j)}\right); \; t>1 \tag{4.1}$$

where:

A_t = the annual dose during the year t from all exposure from all exposure pathways to the organ of reference, in mrem;

$R_t^\star$ = the radiation dose equivalent in year to the organ of reference from all internal and external exposure pathways from intake and exposure in the year t, in mrem; and

$R_{j,k}$ = the radiation dose equivalent commitment to year k to the organ of reference from internal exposure pathways from intake in previous year j, in mrem (Kennedy et al. 1979).

The summation term represents the dose equivalent delivered to the organ of reference, in year t, from radionuclides deposited in the organ during all years since the start of continuous exposure. The annual dose, A_t, is calculated for each organ of concern for values of t from 1 to 50, and the maximum annual dose is determined by inspection. The radionuclide inventories in soil are adjusted for radioactive decay and daughter-product buildup during the 50-year calculation period, but are not increased by continuing biotic transport.

The parameters used for the calculation of radiation doses from the consumption of foods grown in or on contaminated soil are given in Table 4.1-1. Only that fraction of a total diet grown locally is included in this table. This fraction is derived from the fraction of a year that is considered to be the growing season (or the storage potential) for each type of food.

4.2 DOSE CALCULATIONS FOR HUMAN INTRUSION SCENARIOS

Doses to the maximum-exposed individual for the human intrusion scenario, defined in Section 3.1, are calculated using the MAXI computer program. The surface contamination levels (pCi/m^2) for the intruder-agricultural scenario are given in Table 3.1-1 for waste spectra 1 and 2. The maximum-exposed individual is assumed to reside on an 1800 m^2 site. He is exposed by inhalation of resuspended radionuclides, ingestion of garden crops grown in the soil, and direct exposure to penetrating radiation. To account for the small surface area contaminated by the intruder in this scenario, the individual is assumed to ingest only 60 kg of assorted vegetables grown in the contaminated surface soil. No contaminated eggs or meat products are assumed to be consumed from this site. The individual is also assumed to inhale dust with an airborne concentration of 2×10^{-6} g/m^3 for 8 hours per day 5 days per week, or 2000 h/yr. In addition, he is exposed to penetrating radiation for 2000 hours per year. Doses are calculated for total body, bone, lung, thyroid, and the lower large intestine (GI-LLI) of the maximum-exposed individual.

The resulting maximum annual doses and the year during continuous exposure in which the doses peak are listed in Table 4.2-1 for the radionuclides of waste spectra 1 and 2. For both waste spectra, the dominant exposure pathway is direct exposure resulting from Cs-137 and its daughter, Ba-137m. The maximum annual dose from external emitters is the largest in the first year. The resulting maximum annual total body doses are 28 rem for waste spectrum 1 and 20 rem for waste spectrum 2. A complete listing of the maximum annual doses for each organ by radionuclide is given in Appendix C.

4.3 INTRUSION AND ACTIVE BIOTIC TRANSPORT DOSE CALCULATIONS

Doses to the maximum-exposed individual for the intrusion and active biotic transport scenario, defined in Section 3.2, are calculated using the MAXI computer program. The surface contamination levels (pCi/m^2), resulting from this scenario are given in Table 3.2-5 for waste spectra 1 and 2. The maximum-exposed individual residing on a site contaminated under the intrusion and active biotic transport scenario is exposed by inhalation of resuspended radionuclides, ingestion of garden and farm crops grown in the soil,

TABLE 4.1-1. Parameters Used for Calculation of Radiation Doses from Consumption of Foods

Food	Growing Period (days)	Yield (kg/m^2)	Holdup (days)(a)	Consumption (kg/year)(b)
Leafy vegetables	90	1.50	1	30
Other above-ground vegetables	60	0.70	1	30
Potatoes	90	4.00	10	110
Other root vegetables	90	5.00	1	72
Berries	60	2.70	1	30
Melons	90	0.80	1	40
Orchard fruit	90	1.70	10	265
Wheat	90	0.72	10	80
Other grain	90	1.40	1	8
Eggs	90	0.84(c)	2	30
Milk	30	1.30(c)	2	274(d)
Beef	90	0.84(c)	15	40
Pork	90	0.84(c)	15	40
Poultry	90	0.84(c)	2	18

(a) Time between harvest and consumption.

(b) Only that fraction of the diet grown locally, and therefore potentially contaminated, is listed. Consumption by the maximum-exposed individual is assumed.

(c) Yield of animal feeds (i.e., grain or pasture grass).

(d) Units of liters/year.

TABLE 4.2-1. Maximum Annual Doses to the Maximum-Exposed Individual from the Intruder-Agriculture Scenario[a]

Waste Spectrum	Maximum Year[b]	Organ of Reference	Dominant Radionuclide Contributors To Dose	Dominant Exposure Pathway	Maximum Annual Organ Dose (rem)
1[c] (Past Wastes)	1	Total-body	Cs-137 + D[d]	External	28
	1	Bone	Cs-137 + D	External	28
	1	Lungs	Cs-137 + D	External	28
	1	Thyroid	Cs-137 + D	External	28
	1	GI-LLI	Cs-137 + D	External	28
2[e] (Future Wastes)	1	Total-body	Cs-137 + D	External	20
	1	Bone	Cs-137 + D	External	20
	1	Lungs	Cs-137 + D	External	20
	1	Thyroid	Cs-137 + D	External	20
	1	GI-LLI	Cs-137 + D	External	20

(a) The doses are calculated over a 50-year continuous exposure period for the waste spectra shown in Tables 4.1-1 and 4.2-5 starting 100 years after closure of the low-level waste burial ground.

(b) The year in which the maximum annual dose occurs during the 50-year continuous exposure period, starting 100 years after final closure of the LLW waste burial ground.

(c) Waste Spectrum 1 was based on the current mixture and specific activity of LLW radionuclides (U.S. Nuclear Regulatory Commission 1981), with an assumed 35-year container decomposition half-time.

(d) The +D notation indicates that the decay energy of a short-lived daughter product is included.

(e) Waste Spectrum 2 was based on estimates of future LLW mixtures and specific activities (U.S. Nuclear Regulatory Commission 1981), with an assumed 70-year container decomposition half-time.

and direct exposure to penetrating radiation. The entire individual's diet, including eggs and meat products, is assumed to be grown in or on contaminated soil. The individual is assumed to inhale dust with a concentration of 2×10^{-6} g/m^3 for 8 hours per day, 5 days per week or 2000 hours per year. The individual is assumed to be exposed for 2000 hours per year to penetrating radiation from the contaminated soil. As in the human intrusion scenario, doses are calculated for total body, bone, lungs, thyroid, and the lower large intestine (GI-LLI) of the maximum-exposed individual.

The resulting maximum annual doses and the year during continuous exposure in which the doses peak are given in Table 4.3-1 for the radionuclides of waste spectra 1 and 2. For both waste spectra, the dominant exposure pathway for total body and bone is from ingestion of Sr-90 in the food crops grown in or on the contaminated soil. The doses to the remaining organs are controlled by direct exposure to Cs-137 and its daughter, Ba-137m. The critical organ or organ receiving the largest dose for both waste spectra is bone. Calculated maximum annual doses to bone are 15 rem for waste spectrum 1, and 13 rem for waste spectrum 2. A complete listing of the maximum annual doses for each organ by radionuclide is given in Appendix C.

4.4 COMPARISON OF RESULTS

A comparison of the maximum annual dose results for the human intrusion and biotic transport scenarios is given in Table 4.4-1. Again, it should be noted that both sets of doses were calculated using the same pathway analysis models so that a direct comparison could be made. However, the magnitude of the doses are less important than their relative ratio because of uncertainties in many of the parameters. For waste spectrum 1, the ratio of the critical organ doses for the biotic transport scenario to the human intrusion scenario is 0.5. For waste spectrum 2, the critical organ dose ratio (biotic transport to human intrusion) is 0.6. These results indicate that, for the reference arid site, the dose resulting from biotic transport may be within a factor of two of the dose resulting from human intrusion scenarios.

The doses calculated for the human intrusion scenario were based on the waste spectra for the western U. S. and the intruder-agriculture scenario as defined in the DEIS for 10 CFR Part 61 (U. S. Nuclear Regulatory Commission 1981). However, exposure pathway assumptions and dose pathway models were different from those used in the DEIS and resulting doses are slightly different. The NRC total-body dose result for waste spectrum 2, (for the total U. S., and for the intruder-agricultural scenario at 100 years after site closure) is 5.1 rem (U. S. Nuclear Regulatory Commission 1981, p. 4-19). The total-body dose of 20 rem for this study, Table 4.4-1, indicates that the two approaches produce different but relatively similar results.

TABLE 4.3-1. Maximum Annual Doses to the Maximum-Exposed Individual from the Intrusion and Active Biotic Transport Scenario[a]

Waste Spectrum	Maximum Year[b]	Organ of Reference	Dominant Radionuclide Contributors To Dose	Dominant Exposure Pathway	Maximum Annual Organ Dose (rem)
1[c] (Past Wastes)	30	Total-body	Sr-90 + D[d]	Ingestion	3.7
	32	Bone	Sr-90 + D	Ingestion	15
	3	Lungs	Cs-137 + D	External	0.22
	3	Thyroid	Cs-137 + D	External	0.38
	1	GI-LLI	Cs-137 + D	External	0.20
2[e] (Future Wastes)	30	Total-body	Sr-90 + D	Ingestion	3.1
	32	Bone	Sr-90 + D	Ingestion	13
	3	Lungs	Cs-137 + D	External	0.18
	3	Thyroid	Cs-137 + D	External	0.31
	1	GI-LLI	Cs-137 + D	External	0.17

(a) The doses are calculated over a 50-year continuous exposure period for the waste spectra shown in Tables 4.1-1 and 4.2-5 starting 100 years after closure of the low-level waste burial ground.

(b) The year in which the maximum annual dose occurs during the 50-year continuous exposure period, starting 100 years after closure of the LLW waste burial ground.

(c) Waste Spectrum 1 was based on the current mixture and specific activity of LLW radionuclides (U.S. Nuclear Regulatory Commission 1981), with an assumed 35-year container decomposition half-time.

(d) The +D notation indicates that the decay energy of a short-lived daughter product is included.

(e) Waste Spectrum 2 was based on estimates of future LLW mixtures and specific activities (U.S. Nuclear Regulatory Commission 1981), with an assumed 70-year container decomposition half-time.

TABLE 4.4-1. Results Comparison for Human Intrusion and Intrusion and Active Biotic Transport Scenarios

	Human Intrusion Scenario		Biotic Transport Scenario		
Waste Spectrum	Critical Organ	Maximum Annual Dose (rem)	Critical Organ	Maximum Annual Dose	Ratio (Biotic/Human)
1	Total Body	28	Bone	15	0.54
2	Total Body	20	Bone	13	0.65

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5.0 DISCUSSION

While the dose estimates obtained in this study are preliminary and further work is needed to refine the biotic transport model, the results do provide a useful "order of magnitude" estimate of the potential impact of biotic transport. The major result presented in Section 4, that an intrusion and active biotic transport scenario results in doses that are only about a factor of two less than doses from a human intrusion scenario, is quite significant. While the total surface concentration of radionuclides resulting from the biotic transport scenario is less than that which resulted from human intrusion, two conditions are identified as controlling the dose results. First, the surface area contaminated over a burial ground was substantially larger for the biotic transport scenario (70 ha versus 0.18 ha). This condition was reflected in the biotic transport exposure scenario by assuming that the maximum-exposed individual's entire diet came from the site, while only 60 kg/yr was raised onsite for the human intrusion scenario. Second, the resulting radionuclide mixture at the surface was different for biotic transport than for human intrusion. Root penetration by native plants resulted in the selective long-term accumulation of the more biologically available radionuclides at the trench surface. Of most importance in the internal organ dose calculation was Sr-90.

Because of the lack of data in several key areas, it became necessary in the course of this assessment to make several assumptions that directly influenced the results. Thus, this assessment of the potential magnitude of intrusion and active biotic transport at the reference arid site is considered to be a preliminary "order of magnitude" assessment. Key assumptions that may have influenced the results from this study include the following:

- To model waste availability for past and future wastes we assumed container (waste form) decomposition half-times of 35 and 70 years.
- We assumed that all of the radionuclides released during container decomposition were in a chemical form that was available for biotic transport.
- The use of a "composite" animal community may not adequately represent the conditions at a specific arid site. Within this assumed community, we made estimates of representative animal population densities, the volume of soil/waste moved per year, and potential burrow depths. We further assumed that all material moved by burrowing activities reached the soil surface. Further information on belowground redistribution of material by animals would make the model more complex and potentially more complete.
- We assumed that the standard "agricultural" concentration ratios were applicable for determination of radionuclide concentrations of native plants whose roots enter the waste zone.

- We had to develop plant root biomass and depth distributions based on incomplete data.

- The exposure scenarios for both human intrusion and biotic transport require careful review. The assumptions made for this study are reflective of our best judgement based upon similar assumptions made in other published work. These assumptions should be carefully evaluated since they are intended to be reasonably "conservative" and not worst case.

- We assumed that the vegetative cover remained intact and was adequate to control erosion. If erosion were to be significant, then the assumed accumulation of contaminants at the surface may be less and so may the resulting dose to man according to this scenario. Substantial erosion, perhaps as accelerated by the action of burrowing animals, may, under a different scenario, increase the dose to an intruder residing over the burial trench. This may be accomplished by reducing the trench cover thickness. Also, dose to offsite residents may require evaluation if surface contaminants are moved offsite by secondary processes (wind and water erosion, animals, etc.).

- The 100 year elapsed time from site closure to human intrusion was based on previously published scenarios. Alternative time spans may alter the relative importance of the two scenarios.

We are satisfied that the structure of the model for intrusion and active transport is sufficiently developed at this stage to be useful as a tool in additional efforts focused on parameter values. The next step in the assessment of biotic transport at a western site should be to conduct a sensitivity analysis to evaluate the influence and effects of the previously listed assumptions and initial parameter values. Results of these efforts would lead to identification and evaluation of the data base for "key" parameters. Improved data bases should be obtained for "key" parameters. Parameter and model refinement would produce an assessment tool that could play a significant role in formulating regulations and management practices at low level waste disposal at sites in the arid West.

The lack of potential importance of biotic transport at a low-level disposal site as reported in earlier assessment studies is not confirmed by the "order-of-magnitude" estimate presented in this report. Results indicate that biotic transport has the potential to influence low-level disposal site performance and movement of radionuclides to locations where they can enter pathways to man.

APPENDIX A

ANIMAL SPECIES OBSERVED AT WASTE BURIAL SITES AND MAXIMUM ROOTING DEPTH

TABLE A.1. Animal Species Observed at Waste Burial Sites

Animal Category	Species	Source of Information	Type of Information Obtained
Ground squirrel	*Spermophilus townsendii*	Alcorn (1940)	Animal density; burrow depth, diameter, and length
Ground squirrel	*Spermophilus mohavensis*	Bartholomew and Hudson (1961)	Burrow depth and length
Ground squirrel	*Spermophilus townsendii*	Davis (1939)	Burrow diameter
Ground squirrel	*Spermophilus tridecemlineatus*	Desha (1966)	Burrow density, depth, and length
Ground squirrel	*Spermophilus beecheyi*	Fitch (1948)	Animal density; burrow density and depth
Ground squirrel	*Spermophilus tridecemlineatus*	Johnson (1917)	Burrow depth and length
Ground squirrel	*Spermophilus richardsonii*	Michener (1978)	Animal density
Ground squirrel	*Spermophilus tridecemlineatus*	Rongstad (1965)	Animal density and burrow depth
Ground squirrel	*Spermophilus columbianus*	Shaw (1926)	Burrow depth, diameter, and length
Ground squirrel	*Spermophilus tridecemlineatus* and *Spermophilus franklinii*	Wade (1930)	Burrow depth
Pocket mouse	*Perognathus fasciatus*	Criddle (1915)	Burrow depth and length
Pocket mouse	*Perognathus intermedius* and *Perognathus penicillatus*	Hoover et al. (1977)	Animal density
Pocket mouse	*Perognathus parvus*	Landeen and Mitchell (1981)	Burrow depth and volume
Pocket mouse	*Perognathus baileyi* and *Perognathus pricei*	Reynolds and Haskell (1949)	Animal density
Pocket mouse	*Perognathus lordi*	Scheffer (1938)	Burrow depth and diameter
Pocket mouse	*Perognathus parvus*	Schreiber (1978)	Animal density and burrow depth

TABLE A.1. Continued

Animal Category	Species	Source of Information	Type of Information Obtained
Kangaroo rat	*Dipodomys microps*	Anderson and Allred (1964)	Burrow depth and length
Kangaroo rat	*Dipodomys merriami*	Bienek and Grundmann (1971)	Burrow depth and length
Kangaroo rat	*Dipodomys nitratoides*	Culbertson (1946)	Burrow depth and diameter
Kangaroo rat	*Dipodomys ingens*	Grinnell (1932)	Animal density; burrow depth, length, and diameter
Kangaroo rat	*Dipodomys venustus*	Hawbecker (1940)	Burrow depth and length
Kangaroo rat	*Dipodomys spectabilis*	Holdenried (1957)	Animal density
Kangaroo rat	*Dipodomys microps* and *Dipodomys merriami*	Kenagy (1973)	Burrow depth and diameter
Kangaroo rat	*Dipodomys merriami*	Reynolds (1958)	Animal density; burrow density, length, and volume
Kangaroo rat	*Dipodomys ordii* and *Dipodomys merriami*	Schroder and Rosenzweig (1975)	Animal density
Kangaroo rat	*Dipodomys heermanni*	Tappe (1941)	Burrow depth and diameter
Kangaroo rat	*Dipodomys spectabilis*	Vorhies and Taylor (1922)	Burrow depth and diameter
Pocket gopher	*Geomys bursarius*	Axthelm and Lee (1976)	Burrow depth
Pocket gopher	*Geomys bursarius*, *Pappogeomys castanops*, and *Thomomys bottae*	Best (1973)	Burrow depth and diameter
Pocket gopher	*Geomys*	Buechner (1942)	Amount of soil moved to surface
Pocket gopher	*Geomys breviceps*	Davis et al. (1938)	Burrow depth and diameter
Pocket gopher	*Thomomys talpoides*	Ellison (1946)	Animal density and amount of soil moved to surface
Pocket gopher	*Thomomys bottae*	Grinnell (1923)	Amount of soil moved to surface
Pocket gopher	*Thomomys bottae*	Hakonson et al. (1982)	Burrow diameter and length; amount of soil moved

TABLE A.1. Continued

Animal Category	Species	Source of Information	Type of Information Obtained
Pocket gopher	*Pappogeomys castanops*	Hickman (1977)	Burrow depth, diameter and length
Pocket gopher	*Geomys bursarius*	Kennerly (1964)	Animal density and amount of soil moved to the surface
Pocket gopher	*Thomomys bottae*	Miller (1957)	Animal density; burrow density, depth, diameter, length, and amount of soil moved to surface
Pocket gopher	*Thomomys*	Shelford (1929)	Amount of soil moved to surface
Pocket gopher	*Thomomys talpoides*	Winsor and Whicker (1980)	Animal density; burrow depth and diameter; amount of soil moved to surface
Prairie dog	*Cynomys leucurus*	Campbell and Clark (1981)	Animal and burrow density
Prairie dog	*Cynomys leucurus*	Clark (1971)	Burrow density, depth, diameter, and length
Prairie dog	*Cynomys leucurus*	Clark (1977)	Burrow density
Prairie dog	*Cynomys gunnisoni*	Fitzgerald and Lechleitmer (1974)	Animal and burrow density
Prairie dog	*Cynomys ludovicianus*	Koford (1958)	Animal density
Prairie dog	*Cynomys ludovicianus*	Merriam (1902)	Animal density; burrow diameter, length, and volume
Prairie dog	*Cynomys ludovicianus*	Sheets et al. (1971)	Burrow depth, diameter, and length
Prairie dog	*Cynomys ludovicianus* and *Cynomys leucurus*	Stromberg (1978)	Colony size
Prairie dog	*Cynomys ludovicianus* and *Cynomys leucurus*	Tileston and Lechleitner (1966)	Animal and burrow density
Prairie dog	*Cynomys ludovicianus*	Uresk and Bjugstad (1981)	Burrow density
Prairie dog	*Cynomys*	Wilcomb (1954)	Burrow length
Prairie dog	*Cynomys*	Whitehead (1927)	Burrow depth and length

TABLE A.1. Continued

Animal Category	Species	Source of Information	Type of Information Obtained
Badger	*Taxidea taxus*	Lindzey (1976)	Burrow depth and length
Badger	*Taxidea taxus*	Lindzey (1978)	Number of burrows/badger
Badger	*Taxidea taxus*	Messick and Hornocker (1981)	Animal and burrow density
Badger	*Taxidea taxus*	Sargeant and Warner (1972)	Number of burrows/badger
Ants	*Pogonomyrmex owyheei*	Fitzner et al. (1979)	Colony density; burrow depth and amount of soil moved to surface

TABLE A.2. Maximum Observed Rooting Depths of Plants

Species	Annual Grass	Annual Forb	Perennial Grass	Perennial Forb	Shrub	Reference
Bromus tectorum	120					Harris and Goebel 1976
Taeniatherum asperum	120					
Agropyron spicatum			100-200			
Bouteloua gracilis			95			
Muhlenbergia montana			90			Currie and Hammer 1979
Festuca arizonica			120			
Artemesia frigida					122	
Chrysothamnus nauseosus					240	Klepper et al. 1978
Stipa comata			183			Schafer et al. 1979 (Maximum values for several species)
Bromus tectorum	76					
Melilotus officinalis		137				
Tragopogon dubius				137		
Artemisia dracunculus					137	
Salsola kali		240				Cline et al. 1980

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APPENDIX B

BIOPORT COMPUTER PROGRAM LISTING

BIOPORT COMPUTER PROGRAM LISTING

This appendix contains a listing of the BIOPORT computer program. This program calculates the BIOlogical transPORT of radionuclides from a low-level waste burial ground. The biological components considered included both plants and animals. The program is flexible enough to account for various plant and animal communities, and for plant succession and animal activity over time. Source terms for the intrusion and active biotic transport scenario were calculated for waste spectra 1 and 2 using the BIOPORT computer program.

INTRODUCTION

The BIOPORT computer program is used to calculate BIOlogical transPORT of radionuclides from a waste disposal site. Biological components include plants that absorb the material through the roots, translocate it to plant organs (i.e., stems and leaves) and subsequently return it to the soil, and animals that move soil and accompanying radioactivity from various strata to the surface.

The model calculates biological transport for each year of the simulation and for each radionuclide in the waste inventory. For each year the model: 1) simulates decay of the waste inventory and the waste in each stratum, when present; 2) determines the volume of soil brought to the surface from the various strata by animal activity; 3) computes, for each radionuclide in each soil stratum, a new concentration based on soil movement; 4) computes, for each radionuclide in each stratum, a new concentration based on plant activity.

Uptake of radionuclides by a plant is determined by the maximum concentration encountered by the plant roots, and by the concentration ratio (CR) for each element. The radioactivity of the plant is apportioned among the roots and leaves based on the root to shoot ratio and the distribution of the roots within each stratum. Plant biomass is assumed to recycle each year, thus adding radioactive material to each soil stratum.

BIOPORT code and associated subroutines and input files are as follows:

Main Program	BIOPORT
Common Blocks:	ACTVTY DECAY FLAGS NAMES SOURCE
Subroutines Called by Main:	ADJUST CRITTER INVEN PLANT

Subroutines Called by Other Subroutines:	ACHAIN IDNUC RADQA RLIBIN ZEROI ZEROR
Functions:	ASUM EXMO SUMPRD
Radionuclide Master Library:	RMDLIB.BIO
Example of Input Data File:	BIN15.111

```
      PROGRAM BIOPORT
C
C---------------------------------------------------------------------
C
C     BIOPORT - Calculates BIOlogical transPORT of radionuclides from a
C               waste disposal site. Biological components are plant
C               roots which take up the material and distribute it
C               within the plant system (i.e., roots and leaves) and
C               subsequently back into the soil; and an animal component
C               which moves soil and the accommpanying radiation from
C               various strata to the surface.
C               The number of years simulated is variable. There is a
C               maximum of 3 strata (of variable thickness) plus a surface
C               and a repository layer.
C               Community composition is determined on input. It is
C               assumed that plant succession will occur and that animal
C               activity will vary over time. Presently animal activity
C               is assumed to decrease after the first year. Succession
C               in the plant community affects : production (g dry wt/m2/yr),
C               root/shoot ratio, range of roots and the percent of roots in
C               each strata.
C
C     Program is compiled in F4P and is coupled to PLANT, CRITTER
C                and programs for radionuclide decay (Kennedy and
C                Peloquin). Task builder command file : BIORAD
C
C     INPUT  - By line :
C              1)number of years for simulation, frequency for checks,
C              number of strata in overburden, erosion constant for 100
C              years, number of plant species (or communities), number
C              of animal species; 2) depths for each strata; 3) volumes
C              for each strata (m3); 4) conversion for Ci/m3 to Ci/g.
C
C                Package life and radionuclide inventory data includes :
C                1) package life in years (E10.2 format); 2) no. of years
C                of waste storage prior to the beginning of the scenario
C                (E10.2 format); 3) the number of radionuclides in the
C                inventory (I3 format). It is assumed that the input
C                quantity of activity in curies has been decayed for
C                the number of years of prior storage. 4) Each radionuclide
C                in the inventory is then entered on a separate line
C                which contains the following information: atomic symbol,
C                atomic weight in Ci/m3 of waste. The format is: A2, A6,
C                4X, E8.2.  The atomic symbol and atomic weight must be
C                presented in the same notation as the radionuclide master
C                library.
c
C
C              Plant and Animal Data is entered as follows :
C              1) plant name (8 character limit); 2) number of phases in
C              succession, conversion for dry to wet weight; 3) root
```

```
C               to shoot ratio; 4) range of roots in meter intervals;
C               5) % distribution of roots by strata; 6) number of years
C               in each successional phase (start with 0, e.g., 0,10,30);
C               7) production (g/m2) for each successionai phase;
C
C               1) animal name (8 character limit); 2) total amount
C               of dirt moved per year (m3) (maximum), range of movement
C               in meter intervals; 3) % activity for first year and
C               subsequent years; 4) % dirt moved between strata.
C
C               Data for additional plants and animals is repeated in
C               order (i.e., all plants together and then all animals).
C
C               Data in plant lines 3,4,6 and 7 are repeated for each phase;
C               data in plant line 5 is repeated first by strata and then
C               by phase. Data in animal line 4 is repeated by strata.
C
C
C
C       OUTPUT - Output file contains all input parameter values, the
C               radionuclide input inventory and concentrations by
C               strata at specified frequency. A separate file is
C               opened for the total curies by strata at each check
C               year; this file is used (via BPLT) to generate plots.
C               A debug option is available, but should be used ONLY
C               with abridged data sets.
C
C     LATEST REVISION - Aug 10,1982  (M.A.Simmons/R.A.Peloquin)
C
C-------------------------------------------------------------------------
C
      DIMENSION  AMT(10),PMOVE(5,10),PMOIST(10),SOILL(5),DEPTH(5)
      DIMENSION  RANGP(5),QSUM(6),QM(100,6)
C
      COMMON //J,NLYRS,NB
      COMMON /SHRUB/NPLTS,IRANGP(5,10),ISUCC(10),NYSUC(5,10),BIOMAS(5,10),
     1          PROOT(5,10),SROOT(5,5,10),IC,CONV,ACTPLT(5)
C
      COMMON /ANIMAL/NCRIT,IRANGC(10),DIRT(5,10),PACTVE(2,10),DIRTM(5)
C
      BYTE          FILEIN(20),FILOUT(20),DAT(10),HRS(10),FILBUG(20)
      BYTE          FILPLT(20)
C
C                  Names : PNAME(plant);CNAME(critter);
      REAL*8        ANAME,PNAME(10),CNAME(20),DEBUG
C
      INCLUDE 'ACTVTY.FTN'
      INCLUDE 'DECAY.FTN'
      INCLUDE 'FLAGS.FTN'
      INCLUDE 'NAMES.FTN'
      INCLUDE 'SOURCE.FTN'
```

```
C
C
      HA = 10000.                                   ! m2 / hectare.
C
      CALL DATE(DAT)
      CALL TIME(HRS)
      ANAME = 'BIOPORT'
C
      TYPE 100                                      !Parameter filename
      ACCEPT 120,FILEIN
      FILEIN(20) = 0
C
      TYPE 110                                      !Output filename
      ACCEPT 120,FILOUT
      FILOUT(20) = 0
C
      TYPE 105                                      !Plot filename
      ACCEPT 120,FILPLT
      FILPLT(20) = 0
C
      TYPE 115                                      !Debug file?
      ACCEPT 125,DEBUG
      IF(DEBUG .NE. 'Y') GO TO 7
C
      TYPE 140                                      !Debug filename?
      ACCEPT 120,FILBUG
      FILBUG(20) = 0
      TYPE 145                                      !Number of years to monitor
      ACCEPT *,NBUG
C
      OPEN(UNIT=3,NAME=FILBUG,TYPE='NEW')
C
C
   7  CONTINUE
C
      OPEN(UNIT=1,NAME=FILEIN,TYPE='OLD',READONLY)
      OPEN(UNIT=2,NAME=FILOUT.TYPE='NEW')
C
C
C                             Read parameter file :
C                             number years, check pts, number layers,
C                             erosion constant, number plants, number
C                             critters, depths for each strata,
C                             volumes for each strata, conversion for
C                             ci/m3 to ci/gm.
C
      READ(1,*) NYRS,NCHK,NLYRS,ERSION,NPLTS,NCRIT
      READ(1,*) (DEPTH(K),K=1,NLYRS)
      READ(1,*) (VOL(K),K=2,NLYRS+2)
      READ(1,*) CONV
C
```

```
C                                                     !Write to output file
C
      WRITE(2,200) ANAME,DAT,HRS,FILEIN,FILOUT
      WRITE(2,205) NYRS,VOL(1)
      DO 1 K = 1,NLYRS
              WRITE(2,210) DEPTH(K),VOL(K+1),K
  1   CONTINUE
      WRITE(2,215) VOL(NLYRS+2),NLYRS+1,NPLTS,NCRIT,ERSION,CONV
C
      IF(DEBUG .EQ. 'Y') WRITE(3,160)ANAME,DAT,HRS,FILEIN,FILOUT,FILBUG,
      1                             NYRS,NLYRS,NPLTS,NCRIT,ERSION
C
C
      CALL INVEN
C
C
      NLYRS = NLYRS + 2               !Include surface and inventory
C                                      in number of strata.
C
      IF(NPLTS .EQ. 0) GO TO 8
C
C
C                             Read in plant data :
C                             plant name, number of phases in succession,
C                             moisture content, proportion of biomass
C                             in roots, range of roots, distribution
C                             of roots by strata, number of years and
C                             production in each successional phase.
C
      DO 6 I = 1,NPLTS
C
              READ(1,130) PNAME(I)
              READ(1,*)   ISUCC(I),PMOIST(I)
              READ(1,*)   (PROOT(I2,I),I2=1,ISUCC(I))
              READ(1,*)   (RANGP(I2),I2=1,ISUCC(I))
C
              DO 2 I2 = 1,ISUCC(I)             !Convert m's to strata index
                      IRANGP(I2,I) = RANGP(I2) * 2.
  2           CONTINUE
C
              DO 3 I2 = 1,ISUCC(I)
                      READ(1,*)   (SROOT(I2,K2,I),K2=1,IRANGP(I2,I))
  3           CONTINUE
              READ(1,*)   (NYSUC(I2,I),I2=1,ISUCC(I) + 1)
              READ(1,*)   (BIOMAS(I2,I),I2=1,ISUCC(I))
C
              IRANGE = 0
              DO 4 I2 = 1,ISUCC(I)
                      IF(IRANGE .LT. IRANGP(I2,I)) IRANGE = IRANGP(I2,I)
C                                             Convert dry weight to wet.
C                                             And gm/m2 to gm/ha.
```

```
                      BIOMAS(I2,I) = (BIOMAS(I2,I) / (1. - PMOIST(I))) * HA
  4           CONTINUE
C
C
              WRITE(2,220)  PNAME(I)
              WRITE(2,225)  ISUCC(I),PMOIST(I)
              WRITE(2,230)  (NYSUC(I2,I),I2=2,ISUCC(I)+1)
              WRITE(2,235)  (PROOT(I2,I),I2=1,ISUCC(I))
              WRITE(2,240)  (RANGP(I2),I2=1,ISUCC(I))
              WRITE(2,245)  (BIOMAS(I2,I),I2=1,ISUCC(I))
              WRITE(2,250)                     !Heading
              DO 5 K2 = 1,IRANGE
                       WRITE(2,255)  K2,(SROOT(I2,K2,I),I2=1,ISUCC(I))
  5           CONTINUE
C
  6     CONTINUE
C
C                              Read in animal data :
C                              critter name,  total amount of dirt moved,
C                              range of movement, % activity/yr,
C                              % dirt moved between strata.
C
  8     CONTINUE
        IF(NCRIT .EQ. 0) GO TO 18
C
        DO 10 I = 1,NCRIT
C
              READ(1,130) CNAME(I)
              READ(1,*)   AMT(I),RANGC
C
              IRANGC(I) = RANGC * 2.
C
              READ(1,*)   (PACTVE(L,I),L=1,2)
              READ(1,*)   (PMOVE(K2,I),K2=1,IRANGC(I))
C
C
              WRITE(2,260)   CNAME(I)
              WRITE(2,265)   AMT(I),RANGC
              WRITE(2,270)   (PACTVE(L,I),L=1,2)
              WRITE(2,275)                     !Heading for output
              WRITE(2,280)   (PMOVE(K2,I),K2=1,IRANGC(I))
C
 10     CONTINUE
C
C
C                      Maximum amount of dirt moved/critter/layer/year
C
        IF(DEBUG .EQ. 'Y') WRITE(3,165)
C
        DO 15 I = 1,NCRIT
              DO 14 K2 = 1,IRANGC(I)
```

```
                      DIRT(K2,I) = AMT(I) * PMOVE(K2,I)
C
                      IF(DEBUG .EQ. 'Y') WRITE(3,166)I,K2,DIRT(K2,I)
  14            CONTINUE
  15    CONTINUE
C
  18    CONTINUE
C
        CLOSE(UNIT=1)
C
        OPEN(UNIT=1,NAME=FILPLT,TYPE='NEW')                 !File for plot data
C
        IF(DEBUG .EQ. 'Y') WRITE(3,167)           !Heading
C
        DO 20 K = 1,5
                IF(DEBUG .EQ. 'Y') WRITE(3,168) K,VOL(K)
C                                      Zero soil movement totals.
                SOILL(K)  = 0.
                DIRTM(K)  = 0.
  20    CONTINUE
C
        QMAX = 1.0E-25                             !Index to check for max.
C                                                   concentration.
C
C********************************** Start of Simulation ************
C
        DO 99 J = 1,NYRS
C
C                                                  Set index for printout
                IWRT = 0
                NW   = MOD(J,NCHK)
                IF(NW .EQ. 0 .OR. J .EQ. 1) IWRT = 1
C
                NB = 0
                IF(DEBUG .EQ. 'Y' .AND. J .LE. NBUG) NB = 1
                IF(NB .EQ. 1) WRITE(3,185) J
C
                DO 22 K = 1,6
                        QSUM(K) = 0.
  22            CONTINUE
C
C
                T = J                              !Index for ADJUST
                CALL ADJUST(T)
C
C
                TMOVE = 0.                         !Amount of soil moved to surface
C
C
                IF(NCRIT .EQ. 0) GO TO 32
C
```

```
      CALL CRITTER                          !CRITTER
C
C
C
      DO 25 K = 1,NLYRS-1                   !Add soil movement by strata
              SOILL(K) = SOILL(K) + DIRTM(K)
              TMOVE    = TMOVE + DIRTM(K)
 25   CONTINUE
C
      DO 30 K = 2,NLYRS                     !Adjust volumes for soil moved
              VOL(K) = VOL(K) - DIRTM(K-1)
 30   CONTINUE
      VOL(1) = VOL(1) + TMOVE
C
 32   CONTINUE
C
C
C------------------------------------------ Loop for chains ------------
C
      DO 75 IC = 1,NUCS
C
C
C                                           Convert curies to curies/m3
C                                                    (QD)       (QC)
C
              K1 = 1
              IF (NCRIT .EQ. 0) K1 = 2
              DO 35 K = K1,NLYRS
                      QC(IC,K) = QD(IC,K) / VOL(K)
 35           CONTINUE
C
C
C                     Zero surface concentration due to critters
C
              SURFCE = 0.
C
              IF(NCRIT .EQ. 0) GO TO 50
              IF(NB .EQ. 1) WRITE(3,190) IC
C
C
C                     Sum for determining surface conc.
C                     and adjustment of concentration for soil
C                     movement.
C
              IF(NB .EQ. 1) WRITE(3,192) QC(IC,1),QD(IC,1)
              DO 40 K = 2,NLYRS
                      IF(NB .EQ. 1) WRITE(3,191) K-1,DIRTM(K-1),
     1                                 QC(IC,K),QD(IC,K)
                      QT = DIRTM(K-1) * QC(IC,K)
                      QD(IC,K) = QD(IC,K) - QT
                      SURFCE = SURFCE + QT
```

```
  40                  CONTINUE
C
C
C
  50                  CONTINUE                                 !PLANTS
C
                      IF (NPLTS .EQ. 0) GO TO 60
C
                      CALL PLANT
C
C
                      DO 55 K = 2,NLYRS        !Concentration resulting from
C                                               plant decay
                              QD(IC,K) = QD(IC,K) + ACTPLT(K)
  55                  CONTINUE
C
C
C
C
  60                  CONTINUE
C
C                                             Surface concentration
                      QD(IC,1) = QD(IC,1) + SURFCE + ACTPLT(1)
C
                      DO 70 K = 1,NLYRS        !Sums for total curies/strata
                             QSUM(K) = QSUM(K) + QD(IC,K)
  70                  CONTINUE
                      QSUM(NLYRS+1) = QSUM(NLYRS+1) + Q(IC)
C
C
                      IF(NB .EQ. 0) GO TO 75
                      WRITE(3,170)                             !Heading
                      WRITE(3,175)VOL(1),SURFCE,ACTPLT(1),QD(IC,1)
                      DO 65 K = 2,NLYRS
                              WRITE(3,180)K-1,VOL(K),ACTPLT(K),QD(IC,K)
 65                   CONTINUE
C
C
  75          CONTINUE                         !End of Chain loop
C--------------------------------------------------------------------------
C
C
C
              IF(NB .EQ. 1) WRITE(3,195) (VOL(K),K=1,NLYRS)
C
C                                     Check for maximum total curies
C
              DO 80 K = 1,NLYRS - 1
                      IF (QSUM(K) .LE. QMAX) GO TO 80
                      QMAX = QSUM(K)
                      MAXY = J
```

```
  80          CONTINUE
C
              IF (MAXY .NE. J) GO TO 84
C
              DO 82 IC = 1,NUCS
                      DO 81 K = 1,NLYRS
                              QM(IC,K) = QD(IC,K)
  81                  CONTINUE
                      QM(IC,NLYRS+1) = Q(IC)
  82          CONTINUE
C
  84          CONTINUE
C
C
C                                     Erosion occurs at 100 year time steps.
C                                     Insignificant in present model - Aug.
C                                     10, 1982.
C
              NER = MOD(J,100)
              IF(NER .NE. 0) GO TO 85
              SOILL(1) = SOILL(1) - ERSION * J/100
C
  85          CONTINUE
C
C
              IF(IWRT .NE. 1) GO TO 99
              WRITE(2,285)J
              WRITE(2,295)                            !Table Heading
C
              INUC = 0
C
              DO 90 IC = 1,NCH
C
                      IF(NFLAGC(IC) .LE. 0) GO TO 92
                      JCH = NOFNUC(IC)
                      IST = INUC + 1
                      KCH = IST + JCH - 1
C
                      DO 91 IN = IST,KCH
                              WRITE(2,300) ELT(IN),AW(IN),(QD(IN,K),
      1                                    K=1,NLYRS),Q(IN)
  91                  CONTINUE
C
  92                  CONTINUE
                      INUC = INUC + NOFNUC(IC)
C
  90          CONTINUE
              WRITE(2,320) (QSUM(K),K=1,NLYRS+1)
              WRITE(2,325) VOL(1)
C
C
```

```
C                                                 Write sums to plot file
C
              WRITE(1,400) J,(QSUM(K),K=1,NLYRS+1),VOL(1)
C
   99 CONTINUE                                    !End of year simulation
C
C*****************************************************************************
C
C
      DO 97 K=1,NLYRS+1
              QSUM(K) = 0.
   97 CONTINUE
C                                                 Write QD's for maximum year.
C
      WRITE(2,290) MAXY
      WRITE(2,295)                                !Headings
C
      INUC = 0
C
      DO 95 IC = 1,NCH
C
              IF(NFLAGC(IC) .LE. 0) GO TO 94
              JCH = NOFNUC(IC)
              IST = INUC + 1
              KCH = IST + JCH - 1
C
              DO 96 K = 1,NLYRS+1
                      QSUM(K) = QSUM(K) + QM(IC,K)
   96         CONTINUE
C
              DO 93 IN = IST,KCH
                      WRITE(2,300) ELT(IN),AW(IN),(QM(IN,K),
     1                                   K=1,NLYRS+1)
   93         CONTINUE
C
   94         CONTINUE
              INUC = INUC + NOFNUC(IC)
C
   95 CONTINUE
      WRITE(2,320) (QSUM(K),K=1,NLYRS+1)
      WRITE(2,325)  VOL(1)
C
      WRITE(2,305)                                !Heading for strata volumes
      WRITE(2,315) VOL(1)
      DO 98 K = 2,NLYRS
              WRITE(2,310) K-1,SOILL(K-1),VOL(K)
   98 CONTINUE
C
      TYPE 150,ANAME,FILOUT
C
      STOP
```

```
C
C                                     Formats
C
  100 FORMAT(1X,'Name of parameter file.....',$)
  105 FORMAT(1X,'Name of plot file..........',$)
  110 FORMAT(1X,'Name of output file........',$)
  115 FORMAT(1X,'Do you want a DEBUG file...',$)
  120 FORMAT(20A1)
  125 FORMAT(A8)
  130 FORMAT(A8)
  140 FORMAT(1X,'Input DEBUG filename.......',$)
  145 FORMAT(1X,'Input number of years to monitor...',$)
  150 FORMAT(//,1X,'End of program ',A8,'  Output file is ',20A1)
C
  160 FORMAT(T2,'Program :',A8,T20,'Run :',10A1,2X,10A1,/,T2,'Files ',
     1      T8,'Input :',20A1,T36,'output :',20A1,T57,'debug :',20A1,//,
     1      T2,'Simulation Period (years)      :',T42,I4,T52,
     1      'Number of strata               :',T80,I2,/,T2,
     1      'Number of plant communities    :',T42,I4,T52,
     1      'Number of animal species       :',T80,I2,/,T2,
     1      'Erosion constant/100 yrs       :',T42,F6.4,/)
  165 FORMAT(//,T2,'Maximum amount of dirt moved per year',/,T5,
     1      'Critter',T13,'Strata',T22,'Amount',/,T7,'Code',T24,'m3')
  166 FORMAT(T8,I2,T15,I2,T19,G13.6)
  167 FORMAT(//,T2,'---Starting Volumes---',/,T2,'Strata',T12,'Volume',
     1      /,T15,'m3')
  168 FORMAT(T4,I2,T9,G13.6)
  170 FORMAT(//,T2,'Strata',T10,'Volume',T23,'Animals',T37,
     1      'Plant',T54,'QD',/,T12,'m3',T25,'ci',T39,'ci',T54,
     1      'ci',/)
  175 FORMAT(T5,'0',T8,G13.6,T19,G13.6,T33,G13.6,T47,G13.6)
  180 FORMAT(T4,I2,T8,G13.6,T33,G13.6,T47,G13.6)
  185 FORMAT(//,T2,'**** SIMULATION ---- ',I2,' ****',/)
  190 FORMAT(/,T11,'FOR NUCLIDE -- ',I2,//,T2,
     1      'Soil Movement due to Critters / Starting QDs and QCs',/,
     1      T4,'Strata',
     1      T13,'Dirt',T29,'QC',T45,'QD',/,T14,'m3',T27,'ci/m3',T45,
     1      'ci',/)
  191 FORMAT(T6,I2,T10,G13.6,T25,G13.6,T41,G13.6)
  192 FORMAT(T7,'0',T25,G13.6,T41,G13.6)
  195 FORMAT(//,T2,'New Volumes  (m3) :',T21,G13.6,4(/,T21,G13.6))
C
C
  200 FORMAT(//,T10,'Program :',A8,T35,'Run :',10A1,3X,10A1,/,T10,
     1      'Parameter filename :',T32,20A1,T57,'Output filename :',
     1      T75,20A1,//)
  205 FORMAT(T10,'Simulation Period (years)',T40,':',T43,I4,/,T10,
     1      'Strata Identification',T40,':',T44,'DEPTH',T55,'VOLUME',
     1      T67,'CODE',/,T43,'surface',T53,E10.2,T68,'(0)')
  210 FORMAT(T45,F3.1,'m',T53,E10.2,T68,'(',I1,')')
  215 FORMAT(T43,'Inventory',T53,E10.2,T68,'(',I1,')',/,T10,
```

```
     1       'Number of plant communities',T40,':',T45,I2,/,T10,
     1       'Number of animal species   ',T40,':',T45,I2,/,T10,
     1       'Erosion constant (m)/100 yrs ',T40,':',T43,F6.4,/,T10,
     1       'Conversion for m3 to gm  ',T40,':',T43,G13.6,/)
 220 FORMAT(1H1,//,T10,'PLANT-----------',T26,A8)
 225 FORMAT(T10,'Number of Successional Phases =',T40,I6,T60,
     1       'Percent Moisture Content =',T95,F6.4,//)
 230 FORMAT(T10,'Intervals for succession (yrs)',T41,':',T45,5(I6,12X))
 235 FORMAT(T10,'Root/Shoot ratio           ',T44,':',T48,5(G13.6,5X))
 240 FORMAT(T10,'Range of roots (m)       ',T44,':',T48,5(F6.1,12X))
 245 FORMAT(T10,'Biomass during each phase (gm/m3)',T44,':',T48,
     1       5(G13.6,5X))
 250 FORMAT(T10,'% Root distribution by strata',T44,':')
 255 FORMAT(T16,'Strata :',T27,I2,T47,5(F6.4,12X))
 260 FORMAT(//,T10,'CRITTER---------',T26,A8)
 265 FORMAT(T10,'Amount of dirt moved (m3/ha)     =',T45,G13.6,T60,
     1       'Activity range (m) =',T80,F6.1)
 270 FORMAT(T10,'Degree of activity by phase      =',T47,2(F6.4,4X))
 275 FORMAT(/,T10,'Proportion of dirt moved to surface by strata',/,
     1     T12,' 1 ',T19,' 2 ',T26,' 3 ',T33,' 4 ')
 280 FORMAT(T10,F6.4,T17,F6.4,T24,F6.4,T31,F6.4)
 285 FORMAT(1H1,T10,'Simulation for YEAR ',I3,T40,'Total Curies / Ha',
     1       //)
 290 FORMAT(1H1,T10,'Simulation for YEAR ',I3,T40,'Maximum Year',//)
 295 FORMAT(T44,'Strata',T67,'Available',T77,'Contained',/,T12,
     1      'Element',T27,'Surface',T39,'0-.5 m',T48,'.5-1 m',
     1       T58,'1-1.5 m',T67,'Inventory',T77,'Inventory',/)
 300 FORMAT(T14,A2,1X,A6,T25,E10.2,T35,E10.2,T45,E10.2,T55,E10.2,
     1       T65,E10.2,T75,E10.2)
 305 FORMAT(1H1,//,T10,'Strata',T18,'Soil Moved',T30,'Final Volume',/,
     1       T22,'m3',T35,'m3',/)
 310 FORMAT(T13,I2,T17,G13.6,T30,G13.6)
 315 FORMAT(T14,'0',T30,G13.6)
 320 FORMAT(/,T14,'Total',T25,E10.2,T35,E10.2,T45,E10.2,T55,E10.2,
     1       T65,E10.2,T75,E10.2)
 325 FORMAT(/,T14,'Surface Volume (m3/ha) = ',E12.4)
C
 400 FORMAT(1X,I3,7(2X,E12.4))
C
C
C
     END
```

```
C-----------------------------------------------------------------------
C    ACTVTY                        CODED BY RAP                08-04-82
C-----------------------------------------------------------------------
C
     COMMON /ACTVTY/ Q(100), QD(100,5), QC(100,5), PDC, CR(100),
    +                VOL(5)
C
C      Q(100)        - ACTIVITY IN RELEASE INVENTORY FOR EACH RADIONU-
C                      CLIDE IN THE MASTER RADIONUCLIDE LIST,  CURIES.
C      QD(100,5)     - RELEASE ACTIVITIES FOR EACH RADIONUCLIDE FOR:
C                               1 - SURFACE
C                               2 - LAYER 1
C                               3 - LAYER 2
C                               4 - LAYER 3
C                               5 - INVENTORY
C                       IN CURIES.
C      QC(100,5)     - CONCENTRATION OF RADIONUCLIDE INVENTORY IN EACH
C                      SOIL LAYER (CURIES PER CUBIC METER).
C      PDC           - PACKAGE DECAY CONSTANT (LN 2./PACKAGE LIFE)
C      CR(100)       - CONCENTRATION RATIO FOR EACH RADIONUCLIDE
C      VOL(5)        - MASS OF EACH SOIL LAYER (CUBIC METERS).
C                      DURING THIS TIME STEP.
C


C
C-----------------------------------------------------------------------
C    DECAY                         CODED BY RAP                  06-05-80
C-----------------------------------------------------------------------
C
     COMMON /DECAY/ NUC, NCH, NOFNUC(50), NCHST(50), IFR(2,100),
    + DKF(2,100), AL(100), NCHN(100)
C
C      NUC           - NO. OF RADIONUCLIDES IN THE MASTER LIBRARY RMDLIB
C                      1 <= NUC => 100.
C      NCH           - NO. OF DECAY CHAINS IN THE MASTER LIBRARY RMDLIB
C                      1 <= NCH => 50.
C      NOFNUC(50)    - NO. OF RADIONUCLIDES IN EACH DECAY CHAIN. 1 <=
C                      NOFNUC(I) => 9. WHEN NOFNUC(I) = 1, NO DAUGHTERS.
C      NCHST(50)     - LOCATION IN THE MASTER RADIONUCLIDE LIST OF THE
C                      1ST MEMBER OF EACH CHAIN. 1 <= NCHST(I) => 100.
C      IFR(2,100)    - IFR(1,I) GIVES THE CHAIN MEMBER THAT IS THE 1ST
C                      PRECURSOR TO RADIONUCLIDE I. IFR(2,I) IS LOCATION
C                      OF 2ND PRECURSOR. IFR(1,I) < IFR(2,I) < IMEM(I)
C      DKF(2,100)    - FRACTION OF 1ST AND 2ND PRECURSOR THAT DECAYS TO
C                      THIS RADIONUCLIDE.
C      AL(100)       - RADIOLOGICAL DECAY CONSTANT FOR EACH RADIONUCLIDE
C                      SEC ** -1.
C      NCHN(100)     - CHAIN NUMBER FOR EACH RADIONUCLIDE.
C
```

```
C
C----------------------------------------------------------------------
C     FLAGS                        CODED BY RAP              07-15-82
C----------------------------------------------------------------------
C
      COMMON /FLAGS/  NFLAGC(50) , NFLAG(100), INFLG(100)
C
C       NFLAGC(50)    - CONTROL INTEGER TO INDICATE IF ANY RADIONUCLIDES
C                       IN EACH CHAIN ARE SUPPLIED ON INPUT.
C       NFLAG(100)    - CONTROL INTEGER TO INDICATE IF A RADIONUCLIDE IS
C                       GIVEN IN THE INPUT INVENTORY FOR EACH RADIO-
C                       NUCLIDE IN THE MASTER LIST.
C       INFLG(100)    - CONTROL INTEGER TO INDICATE WHICH MASTER LIST
C                       RADIONUCLIDE HAVE DOSE FACTORS SUPPLIED IN INPUT
C       NOTE:
C             <= 0 -- NO DATA GIVEN
C             > 0  -- DATA GIVEN
C
```

```
C
C----------------------------------------------------------------------
C     NAMES                        CODED BY RAP              07-15-82
C----------------------------------------------------------------------
C
      COMMON /NAMES/  ELT(100),  AW(100), NUCS
C
      REAL*8 AW
C
C
C       ELT(100)      - TWO CHARACTER ELEMENT NAME FOR EACH RADIONUCLIDE
C                       IN THE MASTER RADIONUCLIDE DATA LIBRARY.
C       AW(100)       - SIX CHARACTER ATOMIC WEIGHT SYMBOL FOR EACH RADI-
C                       ONUCLIDE IN THE MASTER RADIONUCLIDE DATA LIBRARY.
C                       ISOMERIC STATES ARE INDICATED BY THE LETTER M AF-
C                       TER THE ATOMIC WEIGHT. DAUGHTER CONTRIBUTIONS ARE
C                       INDICATED BY "+D" AFTER THE ATOMIC WEIGHT AND "M"
C                       IF PRESENT.
C       NUCS          - NO. OF RADIONUCLIDES IN THE MASTER LIBRARY. (SAME
C                       AS NUC OF COMMON BLOCK DECAY.)
C
```

```
C-----------------------------------------------------------------------
C     SOURCE                       CODED BY RAP                08-04-82
C-----------------------------------------------------------------------
C
      COMMON /SOURCE/  NIN,  ELTI(100),  AWI(100), QI(100), PL, PLI
C
      REAL*8 AWI
C
C       NIN           - NO. OF RADIONUCLIDES IN THE INPUT INVENTORY,
C                       1 <= NIN => NUC.
C       ELTI(100)     - CHARACTER NAMES FOR INPUT RADIONUCLIDES. SPELLING
C                       MUST BE IDENTICAL TO MASTER RADIONUCLIDE LIST.
C       AWI(100)      - SIX CHARACTER ATOMIC WEIGHT SYMBOL FOR EACH INPUT
C                       RADIONUCLIDE. SPELLING MUST CORRESPOND TO THE
C                       MASTER LIST SPELLING.
C       QI(100)       - ACTIVITY RELEASE OF EACH INPUT RADIONUCLIDE
C                       AT START OF SCENARIO.
C       PL            - PACKAGE LIFE (YEARS).
C       PLI           - NO. OF YEARS OF PRIOR STORAGE OF WASTE. USED TO
C                       CALCULATE INITITAL PACKAGE DECAY.
C
```

```
      SUBROUTINE ADJUST  (T)
C
C***********************************************************************
C
C  ADJUST CONTROLS RADIOLOGICAL AND PACKAGE DECAY CALCULATIONS.
C
C***********************************************************************
C
C     CALLED BY-- BIOPORT
C     SUBORDINATE ROUTINES--  ACHAIN
C     INPUTS--  T
C     INPUT COMMONS--  ACTVTY, DECAY, FLAGS
C     OUTPUTS-- NONE
C     OUTPUT COMMONS--  ACTVTY
C
C-----------------------------------------------------------------------
C
      INCLUDE 'ACTVTY.FTN'
      INCLUDE 'NAMES.FTN'
      INCLUDE 'DECAY.FTN'
      INCLUDE 'FLAGS.FTN'
C
C
      INUC = 0
C
C     CALCULATE FRACTION OF PACKAGE AVAILABLE--
      AF = 1. - EXP ( -PDC )
C
C
C
C     FOR EACH CHAIN--
      DO 100 IC = 1, NCH
C
C       IF DATA SUPPLIED FOR ANY RADIONUCLIDES IN THIS CHAIN--
        IF (NFLAGC (IC) .LE. 0)  GO TO 300
C
          J = NOFNUC(IC)
          IST = INUC + 1
          K = IST + J - 1
C
C
C         CONVERT CHANGE MEMBERS TO PROPER UNITS FOR ACHAIN (CURIES/TIME)--
C
          DO 101 IN = IST, K
C
            Q(IN) = Q(IN) / AL(IN)
            QD(IN,5) = QD(IN,5) / AL(IN)
            QD(IN,4) = QD(IN,4) / AL(IN)
            QD(IN,3) = QD(IN,3) / AL(IN)
            QD(IN,2) = QD(IN,2) / AL(IN)
            QD(IN,1) = QD(IN,1) / AL(IN)
```

```
C
 101       CONTINUE
C
C          DECAY INVENTORY REMAINING IN PACKAGE--
           CALL ACHAIN  (J, 1., DKF(1,IST), IFR(1,IST), AL(IST), Q(IST),
     +                   Q(IST), 0)
C
C
C          DECAY PREVIOUSLY AVAILABLE INVENTORY--
           CALL ACHAIN (J,1., DKF(1,IST), IFR(1,IST), AL(IST), QD(IST,5),
     +                   QD(IST,5), 0)
C          DECAY LAYER 4--
           CALL ACHAIN (J,1., DKF(1,IST), IFR(1,IST), AL(IST), QD(IST,4),
     +                   QD(IST,4), 0)
C
C          DECAY LAYER 2--
           CALL ACHAIN (J,1., DKF(1,IST), IFR(1,IST), AL(IST), QD(IST,3),
     +                  QD(IST,3), 0)
C
C          DECAY LAYER 1--
           CALL ACHAIN (J,1., DKF(1,IST), IFR(1,IST), AL(IST), QD(IST,2),
     +                  QD(IST,2), 0)
C
C          DECAY SURFACE--
           CALL ACHAIN (J,1., DKF(1,IST), IFR(1,IST), AL(IST), QD(IST,1),
     +                  QD(IST,1), 0)
C
C
C
C
C          CONVERT CURIES/YEAR BACK TO CURIES--
C
           DO 200 IN = IST, K
C
             Q(IN) = Q(IN) * AL(IN)
             QD(IN,5) = QD(IN,5)  * AL(IN)
             QD(IN,4) = QD(IN,4) * AL(IN)
             QD(IN,3) = QD(IN,3) * AL(IN)
             QD(IN,2) = QD(IN,2) * AL(IN)
             QD(IN,1) = QD(IN,1) * AL(IN)
C
C
C
 200       CONTINUE
C
 300 CONTINUE
C
         INUC = INUC + NOFNUC(IC)
C
 100 CONTINUE
C
```

```
C     MOVE AVAILABLE INVENTORY FROM PACKAGE TO INVENTRY LAYER--
C
      DO 500 I = 1, NUCS
C
        QM = AF * Q(I)
        Q(I) = Q(I) - QM
        QD(I,5) = QD(I,5) + QM
C
  500 CONTINUE
C
      RETURN
      END
```

```
C************************************** SUBROUTINE CRITTER **************
C
      SUBROUTINE CRITTER
C
C             Animals move dirt and radioactivity from various layers
C             to the surface. The amount of dirt moved is dependent on
C             the activity cycle of the animal, which generally decreases
C             after the first year.
C
C
      COMMON //J,NLYRS,NB
      COMMON /ANIMAL/NCRIT,IRANGC(10),DIRT(5,10),PACTVE(2,10),DIRTM(5)
C
C
D     TYPE *,'   '
D     TYPE *,'Subroutine CRITTER---year ',J
C
      DO 1 K2 = 1,5
              DIRTM(K2) = 0.           !Amount of dirt moved by all animals
  1   CONTINUE
C
      DO 10 I = 1,NCRIT
C
D             TYPE *,' '
D             TYPE *,'CRITTER  ',I
C
              L1 = J
              IF(J .GT. 1) L1 = 2

C
D             TYPE *,' '
D             TYPE *,'   Source   Amt       Total'
D             TYPE *,'            gm           gm   '
C
              DO 5 K2 = 1,NLYRS
C
                      IF(K2 .GT. IRANGC(I)) GO TO 5
                      DIRTM(K2) = DIRTM(K2) + DIRT(K2,I) * PACTVE(L1,I)
C
D                     TYPE *,K2,DIRT(K2,I) * PACTVE(L1,I),DIRTM(K2)
C
  5           CONTINUE
C
  10  CONTINUE
C
C
D     TYPE *,'Return to MAIN'
C
      RETURN
      END
C
```

```
      SUBROUTINE INVEN
C
C***********************************************************************
C
C   INVEN READS RADIOLOGICAL INVENTORY AND PACKAGE LAMBDA; CONTROLS
C   CHECKING OF INVENTORY AND FLAG SETTING; CALCULATES PACKAGE
C   DECAY CONSTANT, INITIAL PACKAGE DECAY AND INITIAL AVAILABLE
C   INVENTORY; AND CONTROLS QA REPORT PRINTING.
C
C***********************************************************************
C
C     CALLED BY-- BIOPORT
C     SUBORDINATE ROUTINES--  RLIBIN, IDNUC, RADQA
C     INPUTS--  FILE 1
C     INPUT COMMONS--  NONE
C     OUTPUTS-- NONE
C     OUTPUT COMMONS--  ACTVTY, SOURCE
C
C-----------------------------------------------------------------------
C
      INCLUDE 'ACTVTY.FTN'
      INCLUDE 'SOURCE.FTN'
C
      DIMENSION TITLR(20)
C
C
C     READ IN MASTER RADIONUCLIDE LIBRARY--
      CALL RLIBIN (TITLR)

C
C     READ IN PACKAGE LIFE--
      READ (1,100) PL
C
C     READ IN NO. OF YEARS OF PRIOR STORAGE OF WASTE--
      READ (1,100) PLI
C
C     READ NUMBER OF RADIONUCLIDES IN INVENTORY--
      READ (1,200) NIN
C
C     READ INVENTORY--
      DO 1 IN = 1, NIN
        READ (1,300) ELTI(IN), AWI(IN), QI(IN)
    1 CONTINUE
C
C
C     CHECK INVENTORY AND SET FLAGS--
      CALL IDNUC
C
C     CALCULATE PACKAGE DECAY CONSTANT--
      PDC = (ALOG (2.)) / (PL )
```

```
C
C
C     PRINT QA REPORT--
      CALL RADQA (TITLR)
C
C     CALCULATE INITIAL AVAILABLE FRACTION OF PACKAGE--
      AFI = 1. - EXP ( - (PDC * (PLI)))
C
C     CALCULATE INITIAL RELEASE OF EACH RADIONUCLIDE--
C
      DO 700 IN = 1, NUCS
C
        QD(IN,5) = Q(IN) * AFI
        Q(IN) = Q(IN) - QD(IN,5)
C
  700 CONTINUE
C
      RETURN
C
C
C     FORMAT STATEMENTS--
C
  100 FORMAT (E10.2)
  200 FORMAT (I3)
  300 FORMAT (A2, A6, 4X, E8.2)
C
      END
```

```
C***************************************** SUBROUTINE PLANT **************
C
      SUBROUTINE PLANT
C
C             Movement of radionuclides by the plant communities is
C             determined by the highest concentration encountered and
C             by the concentration ratio (CR) for each element.
C             Plant biomass is assumed to recycle each year.
C
      COMMON //J,NLYRS,NB
      COMMON /SHRUB/NPLTS,IRANGP(5,10),ISUCC(10),NYSUC(5,10),BIOMAS(5,10),
     1            PROOT(5,10),SROOT(5,5,10),IC,CONV,ACTPLT(5)
C
      DIMENSION    ROOT(5)
C
      INCLUDE 'ACTVTY.FTN'
C
C
C
      DO 50 I = 1,NPLTS
C
              IF(NB .EQ. 1) WRITE(3,60) I
C
              IP = 0
              DO 5 I2 = 1,ISUCC(I)    !Determine plant production for
C                                     !successional phase.
                      IF(J .GT. NYSUC(I2,I) .AND. J .LE. NYSUC(I2+1,I))
     1                       IP = I2
  5           CONTINUE
C
C                                     !Total root biomass (gm/ha)
              ROOTM = BIOMAS(IP,I) * PROOT(IP,I)
C                                     !Total plant biomass (gm/ha)
              TOTMAS = BIOMAS(IP,I) + ROOTM
C
              DO 10 K2 = 1,IRANGP(IP,I)        !Biomass of roots by strata
                      ROOT(K2) =  ROOTM * SROOT(IP,K2,I)
  10          CONTINUE
C
              PCONC = 0.                       !Initial plant conc = 0
              IS = 0
C
C
              DO 15 K2 = 2,NLYRS               !Determine highest concentration
C                                               encountered by plant roots.
C
                      IF(K2 .GT. IRANGP(IP,I)+1) GO TO 15
                      IF(QC(IC,K2) .GT. PCONC) IS = K2
                      IF(QC(IC,K2) .GT. PCONC) PCONC = QC(IC,K2)
C
  15          CONTINUE
```

```
C
             IF(NB .EQ. 1) WRITE(3,65)TOTMAS,BIOMAS(IP,I),ROOTM,PCONC,IS
C
C                                            Curies per ha. for plant.
             PCONC = (PCONC / CONV) * CR(IC) * TOTMAS
C
C                                            Subtract curies from strata
             QD(IC,IS) = QD(IC,IS) - PCONC
C
C                                            Calculate concentration
C                                            for leaf and root parts.
             DO 20 K2 = 1,IRANGP(IP,I)
                    ACTPLT(K2+1) = PCONC * (ROOT(K2) / TOTMAS)
  20         CONTINUE
             ACTPLT(1) = PCONC * (BIOMAS(IP,I)  / TOTMAS)
C
             IF(NB .NE. 1) GO TO 40
C
             WRITE(3,75) PCONC,CR(IC)
             WRITE(3,80)                                     !Heading for leaf.
             WRITE(3,85) BIOMAS(IP,I),ACTPLT(1)
             WRITE(3,90)                                     !Heading for roots
             DO 30 K2 = 1,IRANGP(IP,I)
                    WRITE(3,85) ROOT(K2),ACTPLT(K2+1)
  30         CONTINUE
C
  40         CONTINUE
C
  50  CONTINUE
C
C
      RETURN
C
C                                            Formats
C
  60  FORMAT(//,T2,'Contribution from PLANT ',T40,':',T42,I2,/)
  65  FORMAT(T2,'Plant biomass   (gm/ha)',T40,':',T42,G13.6,/,
      1      T2,'        (Leaf)     (gm/ha)',T40,':',T42,G13.6,/,
      1      T2,'        (Root)     (gm/ha)',T40,':',T42,G13.6,/,
      1      T2,'Highest soil activity (ci/m3)',T40,':',T42,G13.6,/,
      1      T2,'        (removed from layer)',T40,':',T42,I2)
  75  FORMAT(T2,'Total plant activity (ci/ha)',T40,':',T42,G13.6,//,
      1      T2,'Plant concentration by parts -- CR',T40,':',T42,G13.6,/)
  80  FORMAT(T6,'Leaf',T20,'Activity',/,T5,'gm/ha',T21,'ci/ha',/)
  85  FORMAT(T2,G13.6,T17,G13.6)
  90  FORMAT(/,T6,'Root',T20,'Activity',/,T5,'gm/ha',T21,'ci/ha',/)
C
C
      END
```

```
      SUBROUTINE ACHAIN (NUC, T, DK, IFRM, AL, AM, AO, INTGRL)
C
C***********************************************************************
C
C     ACHAIN CALCULATES DECAY FOR ONE CHAIN
C
C***********************************************************************
C
C     CALLED BY-- ADJUST
C     SUBORDINATE ROUTINES-- ASUM, SUMPRD, ZEROR, EXMO
C     INPUTS-- NUC, T, DK, IFRM, AL, AM, INTGRL
C     INPUT COMMONS-- NONE
C     OUTPUTS-- AO
C     OUTPUT COMMONS-- NONE
C
C-----------------------------------------------------------------------
C
      DIMENSION DK(2,9), IFRM(2,9), AL(9), AM(9), AO(9), A(45), EXPO(9)
C
C     INITIALIZE COEFFICIENT ARRAY TO ZERO--
      N2N = NUC * (NUC-1) / 2 + NUC
      CALL ZEROR (N2N, A)
C
C     DO LOOP ON CHAIN MEMBERS,  MAX = NUC--
      DO 5 J = 1, NUC
C
C       CALCULATE EXPONENTIAL FOR CURRENT NUCLIDE--
        ARG=-AL(J) * T
C
        EXPO(J) = EXP (ARG)
        IF (INTGRL .GT. 0)    EXPO(J) = EXMO (ARG, AL(J) )
C
C       SET STARTING INDEX FOR TERM ARRAY A--
        JJ = J * (J-1) / 2
C
C       SET CHAIN POSITION MINUS ONE--
        J1 = J - 1
C
C
        IF(J1 .LE. 0)   GO TO 4
C
          IMAX = MINO (J1, 2)
         DO 3 M = 1, J1
           DO 2 L = M, J1
             DO 1 I = 1, IMAX
C
               IF (IFRM(I,J) .EQ. L)
     +           A(M+JJ) = A(M+JJ) + DK(I,J) * AL(L) * A(M+L * (L-1)/2)
C
C
    1        CONTINUE
```

```
    2       CONTINUE
C
            A(M+JJ) = A(M+JJ) / (AL(J) - AL(M))
C
    3     CONTINUE
C
    4   CONTINUE
C
        A(J + JJ) = AM(J) - ASUM (J1, A(JJ+1) )
        AO(J)= SUMPRD (J, EXPO, A(JJ + 1) )
C
C       ELIMINATE ALL SMALL QUANTITIES--
        IF (AO(J) .LT. 1.0E-12) AO(J)=0.
C
C
    5 CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE IDNUC
C
C***********************************************************************
C
C     IDNUC IDENTIFIES NUCLIDES IN INPUT INVENTORY
C
C***********************************************************************
C
C     CALLED BY-- MAIN
C     SUBORDINATE ROUTINES-- ZEROI, ZEROR
C     INPUTS-- NONE
C     INPUT COMMONS-- SOURCE, NAMES, DECAY
C     OUTPUTS-- NONE
C     OUTPUT COMMONS-- FLAGS, ACTVTY
C
C-----------------------------------------------------------------------
C
      INCLUDE 'ACTVTY.FTN'
      INCLUDE 'DECAY.FTN'
      INCLUDE 'FLAGS.FTN'
      INCLUDE 'NAMES.FTN'
      INCLUDE 'SOURCE.FTN'
C

C
C  INITIALIZE COUNT INDEX ON UNIDENTIFIED NUCLIDES
C
      ISTOP=0
C
      CALL ZEROI(50,NFLAGC)
      CALL ZEROI(100,NFLAG)
      CALL ZEROR(100,Q)
C
C
C  LOOP ON NUCLIDES INPUT.  TEST AGAINST MASTER LIST.
C
      DO 3 IN=1,NIN
      DO 1 IL=1,NUCS
      ILN=IL
      IF(ELT(IL).NE.ELTI(IN)) GO TO 1
      IF(AW(IL).EQ.AWI(IN)) GO TO 2
    1 CONTINUE
C
C  NO MATCH IN LIBRARY FOR INPUT NUCLIDE.  PRINT NAME OF UNKNOWN NUCLIDE
C
      ISTOP=ISTOP+1
      GO TO 3
    2 NFLAG(ILN)=IN
      NFLAGC(NCHN(ILN))=1
C
C     CONVERT INPUT CONCENTRATION TO CURIES--
```

```
      Q(ILN) = QI(IN) * VOL(5)
C
    3 CONTINUE
      IF(ISTOP.LT.1) RETURN
C
C  PRINT TOTAL NUMBER OF UNKNOWN NUCLIDES AND STOP.
C
      WRITE(5,200) ISTOP
  100 FORMAT(1H0,'UNIDENTIFIED NUCLIDE ',A2,A6)
  200 FORMAT(1H0,'THERE WERE UNIDENTIFIED NUCLIDES, ISTOP =',I4)
      STOP
      END
```

```
      SUBROUTINE RADQA (TITLR)
C
C***********************************************************************
C
C   RADQA PRINTS RADIOLOGICAL INVENTORY INPUT DATA REPORT
C
C***********************************************************************
C
C      CALLED BY-- INVEN
C      SUBORDINATE ROUTINES--  NONE
C      INPUTS--  TITLR
C      INPUT COMMONS--  SOURCE, ACTVTY, FLAGS, DECAY, NAMES
C      OUTPUTS-- PRINTED REPORT
C      OUTPUT COMMONS--  NONE
C
C-----------------------------------------------------------------------
C
       INCLUDE 'SOURCE.FTN'
       INCLUDE 'ACTVTY.FTN'
       INCLUDE 'DECAY.FTN'
       INCLUDE 'NAMES.FTN'
       INCLUDE 'FLAGS.FTN'
C
C
       DIMENSION TITLR(20)
C
C      PRINT RADIONUCLIDE INVENTORY--
       WRITE (2,200)
       WRITE (2,300) (ELTI(I), AWI(I),QI(I), I= 1,NIN)
C
C
C
C      PRINT RADIONUCLIDE MASTER LIBRARY TITLE--
       WRITE(2, 150) TITLR
C
C      PRINT RADIONUCLIDE REPORT--
       WRITE (2,151)
C
       INUC = 0
       DO 500 IC = 1, NCH
C
         IF (NFLAGC(IC) .LE. 0) GO TO 600
C
           J = NOFNUC(IC)
           IST = INUC + 1
           K = IST + J - 1
C
           DO 550 IN = IST, K
C
             WRITE (2,152) ELT(IN),AW(IN),AL(IN),CR(IN),Q(IN)
```

```
C
  550       CONTINUE
  600     CONTINUE
C
          INUC = INUC  + NOFNUC(IC)
C
  500 CONTINUE
C
C
C     PRINT PACKAGE LIFE--
      WRITE (2,100) PL
C
C     PRINT NO. OF YEARS PRIOR STORAGE--
      WRITE (2,153) PLI
C
C
      RETURN
C
C
C     FORMAT STATEMENTS--
C
C
  100 FORMAT (//,' ',T10,'Life of package (years): ', F10.1)
C
  150 FORMAT (1H1,' ',T10,'Title of radionuclide master library:',
     +         /,' ',T42,20A4)
  151 FORMAT (//' ',T10,'Radionuclide parent and daughter ',
     +         'parameters:'//,
     +         ' ',T42,':  ELT. WT.',T53,'DECAY CNST  CONC RATIO  ',
     +         'CURIES')
C
  152 FORMAT (' ',T42,A2,2X,A6,3(E10.3,2X))
C
  200 FORMAT (//,' ',T10,'Radionuclide input inventory',T40,
     +        'ELT. WT.',T53,'(CI/M**3)')
  153 FORMAT (' ',T10,'No. of years of package storage prior '
     +        ,'to beginning of scenario:  ', F10.1)
C
C
  300 FORMAT (' ',T42,A2,2X,A6,E10.3)
C
      END
```

```
      SUBROUTINE RLIBIN (TITLR)
C
C*************************************************************************
C
C   THIS SUBROUTINE READS A MASTER NUCLIDE DATA LIBRARY WITH CHAIN
C   DECAY DATA.
C
C*************************************************************************
C
      INCLUDE 'DECAY.FTN'
      INCLUDE 'NAMES.FTN'
      INCLUDE 'ACTVTY.FTN'
C
      DIMENSION TITLR(20),IT(2),FR(2)
C
      REAL*8 A
C
      OPEN (UNIT=10,NAME='RMDLIB.BIO',TYPE='OLD')
C     INITIALIZE INDICES
      CALL ZEROR (100, AL)
C
      AL2 = ALOG (2.)
      IMO=0
      NCH=0
      NUC=1
C
C  READ TITLE CARD
C
      READ(10,200,END=99) TITLR
C
C   READ AND COUNT NUCLIDE ID AND DECAY DATA.
C
    1 READ(10,100,END=99) E,A,T,IM,IT(1),FR(1),IT(2),FR(2),CRI
C
C  TEST FOR END OF LIBRARY
C
      IF(IM.GT.0) GO TO 2
      NUC=NUC-1
      IF(NUC.GT.300) GO TO 98
      IF(NUC.LT.1) GO TO 98
      NUCS = NUC
C
      CLOSE (UNIT=10)
C
      RETURN
C
C  TEST FOR NEW CHAIN, IM = 1
C
    2 IF(IM.GT.1) GO TO 3
C
C  FIRST MEMBER, NEW CHAIN
```

```
C
      NCH=NCH+1
      NOFNUC(NCH)=1
      IMO=1
      NCHST(NCH)=NUC
      GO TO 4
C
C  DAUGHTER NUCLIDES
C  TEST ORDER
C
    3 IF(IM-IMO.NE.1) GO TO 97
      IMO=IM
      NOFNUC(NCH)=NOFNUC(NCH)+1
      IFR(1,NUC)=IT(1)
      IFR(2,NUC)=IT(2)
      DKF(1,NUC)=FR(1)
      DKF(2,NUC)=FR(2)
C
C  SET DATA FOR CURRENT NUCLIDE.
C
    4 ELT(NUC)=E
 1002 FORMAT (' ',2X,A2,2X,A2)
      AW(NUC)=A
      CR(NUC)=CRI
C
      AL(NUC) = AL2 / T* 365.
C
C     IMEM(NUC)=IM
      NCHN(NUC)=NCH
      NUC=NUC+1
      GO TO 1
C
C  PRINT ERROR MESSAGES AND STOP
C
   97 WRITE(5,500)  NCH,IM
  500 FORMAT(1H1,' DIAGNOSTIC 1: DECAY CHAIN',I4,' HAS IMPROPER ORDER. C
     .URRENT MEMBER INDEX IS',I4)
      STOP
   98 WRITE (5,300)  NUC
  300 FORMAT(1H1,' DIAGNOSTIC 2: IMPROPER NUMBER OF NUCLIDES IN MASTER L
     .IBRARY, NUC=',I8)
      STOP
   99 WRITE(5,400)
  400 FORMAT(1H1,' DIAGNOSTIC 3: END OF FILE ON MASTER LIBRARY UNIT 10')
      STOP
C
C  INPUT DATA FORMATS
C
  100 FORMAT(A2,A6,E10.2,I2,2(I2,F7.4), E10.2)
  200 FORMAT(20A4)
      END
```

```
      SUBROUTINE ZEROI(N,K)
C
C***********************************************************************
C
C     THIS MODULE SETS N VALUES OF ARRAY K TO INTEGER ZERO.
C
C***********************************************************************
C
C     CALLED BY-- IDNUC
C     SUBORDINATE ROUTINES-- NONE
C     INPUTS-- N
C     INPUT COMMONS-  NONE
C     OUTPUTS-- K
C     OUTPUT COMMONS-- NONE
C
C-----------------------------------------------------------------------
C
      DIMENSION K(1)
C
      DO 1 J=1,N
        K(J)=0
    1 CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE ZEROR(N,A)
C
C***********************************************************************
C
C     THIS MODULE SETS N VALUES OF ARRAY A TO REAL ZERO.
C
C***********************************************************************
C
C     CALLED BY-- RLIBIN, IDNUC
C     SUBORDINATE ROUTINES-- NONE
C     INPUTS-- N
C     INPUT COMMONS-- NONE
C     OUTPUTS-- A
C     OUTPUT COMMONS-- NONE
C
C-----------------------------------------------------------------------
C
      DIMENSION A(1)
C
      DO 1 J=1,N
        A(J)=0.
    1 CONTINUE
C
      RETURN
      END
```

```
      FUNCTION ASUM(J,A)
C
C***********************************************************************
C
C     THIS FUNCTION SUMS J ELEMENTS OF THE ARRAY A.
C
C***********************************************************************
C
C     CALLED BY-- ACHAIN
C     SUBORDINATE ROUTINES-- NONE
C     INPUTS-- J, A
C     INPUT COMMONS-- NONE
C     OUTPUTS-- ASUM
C     OUTPUT COMMONS--
C
C-----------------------------------------------------------------------
C
      DIMENSION A(1)
C
      ASUM=0.
      IF(J.LE.0) GO TO 2
C
      DO 1 I=1,J
        ASUM=ASUM+A(I)
    1 CONTINUE
C
    2 RETURN
      END
```

```
      FUNCTION EXMO(ARG,AL)
C
C*************************************************************************
C
C     THIS FUNCTION CALCULATES (1-EXP(ARG))/AL FOR NEGATIVE ARG
C
C*************************************************************************
C
C     CALLED BY-- ACHAIN
C     SUBORDINATE ROUTINES-- NONE
C     INPUTS-- ARG, AL
C     INPUT COMMONS-- NONE
C     OUTPUTS-- EXMO
C     OUTPUT COMMONS-- NONE
C
C-------------------------------------------------------------------------
C
      IF(ARG.GT.0.0)GO TO 99
C
      IF (-ARG .LE. 0.001)    GO TO 2
C
        EXMO=(1.0-EXP(ARG))/AL
C
      GO TO 3
    2 CONTINUE
C
        I=-IFIX(ALOG10(-ARG))
        I=8-I
        IF(I.LT.2)I=2
        TERM=-ARG
        EXMO=-ARG/AL
C
        DO 1 IT=2,I
          TERM=(TERM*ARG)/FLOAT(IT)
          EXMO=EXMO+TERM/AL
1       CONTINUE
C
    3 CONTINUE
C
      RETURN
C
99    WRITE(5,100)ARG
100   FORMAT(' ERROR IN FUNCTION EXMO, POSITIVE ARG=',1PE10.3)
      STOP
      END
```

```
      FUNCTION SUMPRD(J,A,B)
C
C***********************************************************************
C
C     THIS FUNCTION GENERATES THE SUM OF TERM BY TERM PRODUCTS OF
C     TWO ARRAYS.
C
C***********************************************************************
C
C     CALLED BY-- ACHAIN
C     SUSBORDINATE ROUTINES-- NONE
C     INPUTS-- J, A, B
C     INPUT COMMONS-- NONE
C     OUTPUTS-- SUMPRD
C     OUTPUT COMMONS-- NONE
C
C-----------------------------------------------------------------------
C
      DIMENSION A(1),B(1)
C
      SUMPRD=0
C
      DO 1 I=1,J
        SUMPRD=SUMPRD+A(I)*B(I)
    1 CONTINUE
C
      RETURN
      END
```

RADIONUCLIDE MASTER DATA LIBRARY - RMDLIB.BIO

The RMDLIB.BIO library contains all radiological decay data and the concentration factors used by BIOPORT. The first section contains radionuclides which are not members of decay chains, and also radionuclides singled out from the chains with the "+D" (plus daughter) designation. Data entries in the first section are arranged by increasing atomic number. The second section of the library contains radionuclides organized into decay chains, ordered under the radionuclides highest in the chain. RMDLIB.BIO contains the following information on each radionuclide:

Column 1	Alphabetic elemental symbol
Column 2	Atomic weight, also metastable and/or "+D"
Column 3	Radiological half-life, days
Column 4	Relative position in decay chain
Column 5	Precursor in decay chain
Column 6	Branching ratio for primary precursor
Column 7	Alternate precursor in decay chain
Column 8	Branching ratio from alternate precursor
Column 9	Food transfer coefficient for plants: pCi per gram plant (wet)/pCi per gram soil (dry)

The RMDLIB.BIO FORTRAN format is (A2, A6, E10.2, 2I2, F7.4, I2, F7.4, E10.2).

RMDLIB.BIO

```
 RADIONUCLIDE MASTER DATA LIBRARY FOR BIOPORT, 29 JULY 82, RAP/WEK
H 3         4.51E+3 1 0           0           0.0
C 14      2.091E+6 1 0           0           0.0
FE55        9.86E+2 1 0           0           4.0E-4
CO60        1.92E+3 1 0           0           9.4E-3
NI59        2.74E+7 1 0           0           1.9E-2
NI63        3.51E+4 1 0           0           1.9E-2
SR90+D      1.04E+4 1 0           0           2.0E-1
CS137+D     1.10E+4 1 0           0           2.0E-3
U 235+D     2.59E11 1 0           0           2.5E-3
U 238+D     1.65E12 1 0           0           2.5E-3
NP237+D     7.82E+8 1 0           0           2.5E-3
PU237       4.56E+1 1 0           0           2.5E-4
PU241+D     5.26E+3 1 0           0           2.5E-4
SR90        1.04E+4 1 0           0           2.0E-1
Y 90        2.67E+0 2 1 1.0       0           2.5E-3
NB94        7.30E+6 1 0                       9.4E-3
TC99        7.78E+7 1 0                       2.5E-1
I 129       5.71E+9 1 0           0           2.0E-2
CS135       8.40E+8 1 0           0           2.0E-3
CS137       1.10E+4 1 0           0           2.0E-3
BA137M      1.77E-3 2 1 0.946     0           5.0E-3
U 235       2.59E11 1 0           0           2.5E-3
TH231       1.06E+0 2 1 1.0       0           4.2E-3
PA231       1.19E+7 3 2 1.0       0           2.5E-3
AC227       7.95E+3 4 3 1.0       0           2.5E-3
TH227       1.87E+1 5 4 0.9862 0              4.2E-3
FR223       1.51E-2 6 4 0.0138 0              0
RA223       1.14E+1 7 5 1.0       6 1.0       1.4E-3
NP237       7.82E+8 1 0           0           2.5E-3
PA233       2.70E+1 2 1 1.0       0           2.5E-3
U 233       5.79E+7 3 2 1.0       0           2.5E-3
TH229       2.68E+6 4 3 1.0       0           4.2E-3
RA225       1.48E+1 5 4 1.0       0           1.4E-3
AC225       1.00E+1 6 5 1.0       0           2.5E-3
U 238       1.65E12 1 0 0.0       0           2.5E-3
TH234       2.41E+1 2 1 1.0       0           4.2E-3
PA234M      8.13E-4 3 2 1.0       0           2.5E-3
PA234       2.81E-1 4 3 0.0013 0              2.5E-3
PU242       1.41E+8 1 0           0           2.5E-4
NP238       2.18E+0 2 0           0           2.5E-3
PU238       3.21E+4 3 2 1.0                   2.5E-4
CM244       6.61E+3 1 0           0           2.5E-3
PU244       3.02E10 2 0           0           2.5E-4
U 240       5.88E-1 3 2 0.999     0           2.5E-3
PU240       2.39E+6 4 3 1.0       1 1.0       2.5E-4
CM243       1.04E+4 1 0           0           2.5E-3
PU243       2.06E-1 2 0 1.0       0           2.5E-4
AM243       2.70E+6 3 2 1.0       1 0.0024    2.5E-4
NP239       2.36E+0 4 3 1.0       0           2.5E-3
PU239       8.91E+6 5 4 1.0       1 0.9976    2.5E-4
```

```
PU241      5.26E+3 1 0      0           2.5E-4
AM241      1.58E+5 2 1 1.0  0           2.5E-4
                   0
```

BIN15.111 (See first page of BIOPORT code for interpretation of input.)

```
200,10,3,.01,1,6
.5,1.0,1.5
5000,5000,5000,6.5E4
1.7E6
       35.
       20.
 24
H 3          4.00E-02
C 14         4.00E-03
FE55         5.00E-01
NI59         1.70E-03
NB94         5.40E-05
CO60         1.40E+00
NI63         1.40E-01
SR90         4.10E-03
TC99         6.40E-05
I 129        1.70E-04
CS135        6.40E-05
CS137        1.40E+00
U 235        2.90E-05
U 238        2.90E-05
NP237        9.60E-11
PU238        5.20E-04
PU239        2.20E-04
PU240        2.20E-04
PU241        1.40E-02
PU242        9.70E-07
AM241        3.80E-04
AM243        2.30E-05
CM243        4.20E-07
CM244        2.70E-04
Western
2,.85
.5,1
2,2
.80,.05,.05,.10
.65,.15,.10,.10
0,100,500
250,100
Gopher
8.3,1
1.0,.75
.85,.15
Pr Dogs
1.96,2
1.0,.02
.20,.20,.20,.40
Squirrel
.5,2
1,.5
.5,.3,.15,.05
```

```
Poc MIce
.35,2
1,.75
.5,.4,.05,.05
Badgers
.211,2
1,1
.70,.15,.05,.10
Ants
.1,2
1,.1
.70,.10,.10..10
```

APPENDIX C

TABULATION OF MAXIMUM ANNUAL DOSES

TABULATION OF MAXIMUM ANNUAL DOSES

Maximum annual doses to the organs of the maximum-exposed individual were calculated for this study using the MAXI computer program. The exposure pathways considered included ingestion of food products grown in contaminated soil, inhalation of resuspended radionuclides, and direct exposure from contaminated soil. Dose estimates were provided for two radionuclide inventories. These were defined as waste spectrum 1 for past or current low-level waste streams, and waste spectrum 2 for future waste streams. To account for the availability of the waste for biotic transport, two container decomposition half-times were assumed. A 35-year half-time was assumed for past wastes in waste spectrum 1, and a 70-year half-time was assumed for future wastes in waste spectrum 2. The organs for which doses were calculated included total body, bone, lung, thyroid, and the lower large intestine (GI-LLI). Summaries of the calculated doses are shown in Tables C.1 and C.2 for the intruder-agriculture scenario and the intrusion and active biotic transport scenario, respectively. While doses were calculated for all of the radionuclides in the source terms reported in Tables 3.1-1 and 3.2-5, only the significant contributors (1% of the dose to any organ) were included in Tables C.1 and C.2. The year in which the maximum annual dose occurs after the start of continuous exposure was reported for each organ. The dose calculations were performed beginning 100 years after site closure to account for an institutional control period. During this 100 year period, the inventory was modified to account for radioactive decay and daughter product buildup. The inventory was not modified by contributions from continuing biotic transport processes during the 50-year continuous exposure period.

TABLE C.1. Doses by Radionuclide to the Organs of the Maximum-Exposed Individual Resulting from the Intruder-Agriculture Scenario

Organ/ Maximum Year[a]	Radionuclide[b]	Dose From Waste Spectrum 1 (rem)				Dose From Waste Spectrum 2 (rem)			
		Ingestion	Inhalation	External	Total for All Pathways	Ingestion	Inhalation	External	Total for All Pathways
Total-Body (1)	Co-60	2.2×10^{-6}	--[c]	2.4×10^{-3}	2.4×10^{-3}	1.6×10^{-6}	--	1.7×10^{-3}	1.7×10^{-3}
	Sr-90[d]	6.2×10^{-2}	3.2×10^{-8}	6.6×10^{-4}	6.2×10^{-2}	4.5×10^{-2}	2.3×10^{-8}	4.8×10^{-4}	4.5×10^{-2}
	Cs-137[d]	2.3×10^{-1}	3.2×10^{-6}	2.8×10^{1}	2.8×10^{1}	1.7×10^{-1}	2.4×10^{-6}	2.0×10^{1}	2.0×10^{1}
	U-235[d]	4.1×10^{-5}	1.2×10^{-9}	--	4.1×10^{-5}	3.1×10^{-5}	--	--	3.1×10^{-5}
	Am-241	2.7×10^{-6}	4.0×10^{-8}	7.8×10^{-4}	7.8×10^{-4}	1.9×10^{-6}	2.8×10^{-8}	5.6×10^{-4}	5.6×10^{-4}
	Totals	2.9×10^{-1}	3.4×10^{-6}	2.8×10^{1}	2.8×10^{1}	2.1×10^{-1}	2.4×10^{-6}	2.0×10^{1}	2.0×10^{1}
Bone (1)	Co-60	--	--	2.4×10^{-3}	2.4×10^{-3}	--	--	1.7×10^{-3}	1.7×10^{-3}
	Sr-90[d]	2.3×10^{-1}	1.2×10^{-7}	6.7×10^{-4}	2.3×10^{-1}	1.7×10^{-1}	1.0×10^{-7}	4.9×10^{-4}	1.7×10^{-1}
	Cs-137[d]	2.3×10^{-1}	4.5×10^{-6}	2.8×10^{1}	2.8×10^{1}	1.7×10^{-1}	3.3×10^{-6}	2.0×10^{1}	2.0×10^{1}
	U-235[d]	3.5×10^{-4}	9.4×10^{-9}	--	3.5×10^{-4}	2.6×10^{-4}	7.0×10^{-9}	--	2.6×10^{-4}
	Am-241	6.0×10^{-5}	8.8×10^{-7}	7.8×10^{-4}	8.4×10^{-4}	4.3×10^{-5}	6.3×10^{-7}	5.6×10^{-4}	6.0×10^{-4}
	Totals	4.6×10^{-1}	6.4×10^{-6}	2.8×10^{1}	2.8×10^{1}	3.4×10^{-1}	4.6×10^{-6}	2.0×10^{1}	2.0×10^{1}
Lung (1)	Co-60	--	2.52×10^{-9}	2.35×10^{-3}	2.4×10^{-3}	--	1.9×10^{-9}	1.7×10^{-3}	1.7×10^{-3}
	Sr-90[d]	--	1.3×10^{-8}	6.7×10^{-4}	6.7×10^{-4}	--	9.3×10^{-9}	4.9×10^{-4}	4.9×10^{-4}
	Cs-137[d]	3.6×10^{-2}	1.3×10^{-6}	2.8×10^{1}	2.8×10^{1}	2.7×10^{-2}	9.5×10^{-7}	2.0×10^{1}	2.0×10^{1}
	U-235[d]	--	3.1×10^{-6}	--	3.1×10^{-6}	--	2.3×10^{-6}	--	2.3×10^{-6}
	Am-241	--	1.0×10^{-4}	7.8×10^{-4}	7.8×10^{-4}	--	7.3×10^{-5}	5.6×10^{-4}	6.3×10^{-4}
	Totals	3.6×10^{-2}	2.0×10^{-4}	2.8×10^{1}	2.8×10^{1}	2.7×10^{-2}	1.4×10^{-4}	2.0×10^{1}	2.0×10^{1}
Thyroid (1)	Co-60	--	--	2.4×10^{-3}	2.4×10^{-3}	--	--	1.7×10^{-3}	1.7×10^{-3}
	I-129	3.0×10^{-1}	7.0×10^{-7}	6.7×10^{-5}	3.0×10^{-1}	2.2×10^{-1}	5.1×10^{-7}	4.9×10^{-5}	2.2×10^{-1}
	Cs-137[d]	--	--	2.8×10^{1}	2.8×10^{1}	--	--	2.0×10^{1}	2.0×10^{1}
	Totals	3.0×10^{-1}	7.0×10^{-7}	2.8×10^{1}	2.8×10^{1}	2.1×10^{-1}	5.1×10^{-7}	2.0×10^{1}	2.0×10^{1}
GI-LLI (1)	Co-60	--	--	2.4×10^{-3}	2.4×10^{-3}	--	--	1.7×10^{-3}	1.7×10^{-3}
	Sr-90[d]	1.1×10^{-1}	8.5×10^{-9}	6.7×10^{-4}	1.1×10^{-1}	7.8×10^{-2}	6.2×10^{-9}	4.9×10^{-4}	4.9×10^{-4}
	Cs-137[d]	1.2×10^{-2}	6.1×10^{-8}	2.8×10^{1}	2.8×10^{1}	9.2×10^{-5}	4.4×10^{-8}	2.0×10^{1}	2.0×10^{1}
	U-235[d]	1.2×10^{-4}	1.3×10^{-9}	--	1.2×10^{-4}	8.7×10^{-5}	--	--	8.7×10^{-5}
	Am-241	2.9×10^{-4}	3.4×10^{-8}	7.8×10^{-4}	1.0×10^{-3}	2.1×10^{-4}	2.5×10^{-8}	5.6×10^{-4}	7.7×10^{-4}
	Totals	1.2×10^{-1}	1.4×10^{-7}	2.8×10^{1}	2.8×10^{1}	8.8×10^{-2}	1.0×10^{-7}	2.0×10^{1}	2.0×10^{1}

(a) The year in which the maximum annual dose occurs after the start of continuous exposure.

(b) Only significant contributors to dose are included in this table.

(c) Dashes indicate a dose contribution of less than 1×10^{-9} rem.

(d) Short-lived daughters are included.

TABLE C.2. Doses by Radionuclide to the Organs of the Maximum-Exposed Individual Resulting from the Intrusion and Active Biotic Transport Scenario

		Dose From Waste Spectrum 1 (rem)				Dose From Waste Spectrum 2 (rem)			
Organ/ Maximum Year[a]	Radionuclide[b]	Ingestion	Inhalation	External	Total for All Pathways	Ingestion	Inhalation	External	Total for All Pathways
Total-Body	Co-60	8.5×10^{-9}	--[c]	7.8×10^{-7}	7.8×10^{-7}	6.8×10^{-9}	1.6×10^{-11}	6.2×10^{-7}	6.2×10^{-7}
(30)	Sr-90[d]	3.6×10^{0}	7.7×10^{-4}	7.3×10^{-5}	3.6×10^{0}	3.0×10^{0}	6.5×10^{-4}	6.1×10^{-5}	3.0×10^{0}
	Cs-137[d]	2.1×10^{-2}	8.2×10^{-5}	1.0×10^{-1}	1.2×10^{-1}	1.8×10^{-2}	6.8×10^{-5}	8.7×10^{-2}	9.9×10^{-2}
	U-235[d]	6.4×10^{-6}	3.6×10^{-7}	--	6.8×10^{-6}	1.2×10^{-5}	6.6×10^{-7}	--	1.2×10^{-5}
	Am-241	7.6×10^{-6}	3.4×10^{-4}	3.9×10^{-6}	3.4×10^{-4}	6.5×10^{-6}	2.9×10^{-4}	3.4×10^{-6}	2.9×10^{-4}
	Totals	3.6×10^{0}	1.5×10^{-3}	1.0×10^{-1}	3.7×10^{0}	3.0×10^{0}	1.3×10^{-3}	8.7×10^{-2}	3.1×10^{0}
Bone	Co-60	--	--	6.0×10^{-7}	6.0×10^{-7}	--	--	4.8×10^{-7}	4.8×10^{-7}
(32)	Sr-90[d]	1.4×10^{1}	3.1×10^{-3}	6.9×10^{-5}	1.4×10^{1}	1.2×10^{1}	2.6×10^{-3}	5.7×10^{-3}	1.2×10^{1}
	Cs-137[d]	2.3×10^{-2}	1.5×10^{-4}	9.9×10^{-2}	9.9×10^{-2}	1.9×10^{-2}	1.2×10^{-4}	8.3×10^{-2}	1.0×10^{-1}
	U-235[d]	1.0×10^{-5}	5.9×10^{-6}	--	1.6×10^{-5}	1.9×10^{-4}	1.1×10^{-5}	--	1.3×10^{-4}
	Am-241	1.9×10^{-4}	8.7×10^{-3}	3.9×10^{-6}	8.9×10^{-3}	1.7×10^{-4}	7.4×10^{-3}	3.4×10^{-6}	7.6×10^{-4}
	Totals	$.5 \times 10^{1}$	2.0×10^{-2}	9.9×10^{-2}	1.5×10^{1}	1.3×10^{1}	1.7×10^{-2}	8.3×10^{-2}	1.3×10^{1}
Lung	Co-60	--	4.9×10^{-7}	2.8×10^{-5}	2.8×10^{-5}	--	3.9×10^{-7}	2.2×10^{-5}	2.2×10^{-5}
(3)	Sr-90[d]	--	1.3×10^{-5}	1.4×10^{-4}	1.5×10^{-4}	--	1.1×10^{-5}	1.2×10^{-4}	1.3×10^{-4}
	Cs-137[d]	6.9×10^{-3}	6.4×10^{-5}	1.9×10^{-1}	1.9×10^{-1}	5.7×10^{-3}	5.4×10^{-5}	1.6×10^{-1}	1.6×10^{-1}
	U-235[d]	--	4.2×10^{-4}	--	4.2×10^{-4}	--	7.7×10^{-4}	--	7.7×10^{-4}
	Am-241	3.2×10^{-6}	8.6×10^{-3}	4.1×10^{-6}	8.6×10^{-3}	2.7×10^{-6}	7.4×10^{-3}	3.5×10^{-6}	7.4×10^{-4}
	Totals	6.9×10^{-3}	1.7×10^{-2}	1.9×10^{-1}	2.2×10^{-1}	5.7×10^{-3}	1.5×10^{-2}	1.6×10^{-1}	1.8×10^{-1}
Thyroid	Co-60	--	--	2.8×10^{-5}	2.8×10^{-5}	--	--	2.2×10^{-5}	2.2×10^{-5}
(3)	I-129	1.8×10^{-1}	1.6×10^{-4}	1.8×10^{-6}	1.8×10^{-1}	1.5×10^{-1}	1.3×10^{-4}	1.4×10^{-6}	1.5×10^{-1}
	Cs-137[d]	--	--	1.9×10^{-1}	1.9×10^{-1}	--	--	1.6×10^{-1}	1.6×10^{-1}
	Totals	1.8×10^{-1}	1.6×10^{-4}	1.9×10^{-1}	3.8×10^{-1}	1.5×10^{-1}	1.3×10^{-4}	1.6×10^{-1}	3.1×10^{-1}
GI-LLI	Co-60	--	4.9×10^{-9}	3.6×10^{-5}	3.6×10^{-5}	--	3.9×10^{-9}	2.8×10^{-5}	2.8×10^{-5}
(1)	Sr-90[d]	--	9.1×10^{-6}	1.5×10^{-4}	1.5×10^{-5}	--	7.4×10^{-6}	1.2×10^{-4}	1.2×10^{-4}
	Cs-137[d]	--	2.2×10^{-6}	2.0×10^{-1}	2.0×10^{-1}	--	1.8×10^{-6}	1.7×10^{-1}	1.7×10^{-1}
	U-235[d]	1.1×10^{-5}	4.9×10^{-8}	--	1.1×10^{-5}	2.1×10^{-5}	9.0×10^{-8}	--	2.1×10^{-5}
	Am-241	1.8×10^{-5}	8.8×10^{-7}	4.1×10^{-6}	2.2×10^{-5}	1.5×10^{-5}	7.6×10^{-7}	3.5×10^{-6}	1.9×10^{-6}
	Totals	4.4×10^{-5}	1.3×10^{-5}	2.0×10^{-1}	2.0×10^{-1}	4.9×10^{-5}	1.2×10^{-5}	1.7×10^{-1}	1.7×10^{-1}

(a) The year in which the maximum annual dose occurs after the start of continuous exposure.
(b) Only significant contributors to dose are included in this table.
(c) Dashes indicate a dose contribution of less than 1 x 10^{-9} rem.
(d) Short-lived daughters are included.

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The purpose of the work reported here was to estimate the potential dose to man resulting from biotic transport mechanisms at a reference arid low-level waste site. The site description includes waste inventories, site characteristics, and biological communities. Parameter values for biotic transport are based on data reported in current literature. Calculations of radionuclide decay and waste container decomposition are made to estimate the amount of radioactive material available for biotic transport and exposure scenarios 100 years following site closure. One hundred year dose to man estimates based on biotic transport are estimated to be of the same order of magnitude as dose estimates resulting from the more commonly evaluated intrusion-agricultural scenario reported in NRC's DEIS for 10 CFR 61. These results indicate that biotic transport has the potential to influence low-level waste site performance. The reported lack of potential importance of biotic transport at low-level waste sites in earlier assessment studies is not confirmed by the findings presented in this report. Through biotic transport, radionuclides may be moved to locations where they can enter exposure pathways to man.

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