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

Topical Report on Reference Eastern Humid Low-Level Sites

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RELEVANCE OF BIOTIC PATHWAYS TO THE LONG-TERM REGULATION OF NUCLEAR WASTE DISPOSAL:

TOPICAL REPORT ON REFERENCE EASTERN HUMID 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 humid reference low-level waste site in the eastern U.S. 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 500 years following site closure. Calculations of radionuclide decay and waste container decomposition are made to estimate the quantities available for biotic transport. Doses to man are calculated for the biological transport of radionuclides at the reference site after loss of institutional control. These dose estimates are compared to dose estimates we calculated for the intruder-agricultural scenarios reported in the DEIS for 10 CFR 61 (NRC). Dose to man estimates as a result of cumulative biotic transport are calculated 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 findings presented in this report. Through biotic transport, radionuclides can be moved to locations where they can enter exposure pathways to man.

SUMMARY

An order-of-magnitude assessment of the importance of biotic transport at a reference low-level waste disposal site in the humid East indicates that biotic transport processes are potential contributors to site performance and future dose to man. Our calculations indicate that at the reference disposal site, which is similar in physical characteristics to currently operated sites, the resulting dose to man is of the same order-of-magnitude as doses from current assessments of human intrusion scenarios.

Two conditions were identified as controlling the dose in the biotic transport scenario. First, the surface area contaminated over the burial ground was substantially larger for the biotic transport scenario than for the human intrusion 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 that are thought to influence the magnitude of the calculated dose. 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.

CONTENTS

TABLES

FIGURES

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. 1982a). McKenzie et al. (1982b) concluded that doses from biotic transport were potentially the same order-of-magnitude as the intruder agriculture scenario for an arid reference disposal site in the western U.S. This report contains an assessment of the potential magnitude that contributions from biotic transport would make on radiation dose to man for a reference low-level waste disposal site in the humid East. Biotic transport occurs when the actions of plants or animals cause radioactive materials to be transported from a low-level burial ground to a location where the radionuclides can enter into human exposure pathways.

Three types of 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. 1982a). In transport enhancement, plants and animals modify the wastes or waste site such that the potential for radionuclide transport increases. 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, as in McKenzie et al. (1982b), only intrusion and active transport by biota are considered. An initial qualitative assessment indicated that intrusion with active transport is potentially the most important biotic transport mechanism (McKenzie et al. 1982a). 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: 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 through the low-level waste trench cover and onto the trench surface. The resulting soil concentrations of radionuclides can then contribute to the radiation dose to man through a number of exposure pathways. The following exposure pathways are considered in this report: 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 humid site in the eastern U.S. along with its associated plant and animal communities. The assessment includes consideration of long-term events such as plant community succession. Waste inventories and disposal scenarios are examined for both current and future practices, since these will also influence the magnitude of biotic transport.

Section 2 of this report contains a description of the reference disposal site and the surrounding environment. Reference radionuclide inventories called waste spectra are developed for the humid 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 cases with and without biotic transport. A discussion of the results and their implications is contained in Section 5. Also in Section 5, conclusions are drawn from this assessment concerning the relative importance of biotic transport processes at an eastern humid site.

1.1 REFERENCES

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2.0 REFERENCE HUMID SITE DESCRIPTION

To assist in determining the importance of biotic transport at low-level waste (LLW) burial grounds, we have defined a humid reference low level site and waste inventories for the East. The methods used to develop the reference site and waste inventory information are similar to those used in an earlier topical report on a reference low-level site in the arid West (McKenzie et al. 1982, Vol. 2). The site description is constructed to represent conditions at sites located in the midwestern and eastern United States, although not all of the features at the reference humid site are the same as those actually encountered at any specific site. However, the use of representative generic parameters provides a representative basis for analyzing the relative impacts of biotic transport processes.

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

2.1 REFERENCE HUMID SITE LOW-LEVEL WASTE BURIAL GROUND

Four commercial low-level waste burial grounds that have operated or are operating are located in humid areas of the United States. These are: Sheffield, Illinois; West Valley, New York; Morehead, Kentucky; and Barnwell, South Carolina. Although the Sheffield, West Valley, and Morehead sites are now closed, a brief review of these sites and their operational characteristics is included prior to defining the conditions at the reference humid site. The physical and operational characteristics of these four LLW burial grounds are described in a document by Murphy and Holter (1980, Sec. 3.1.1). These sites were designed to receive 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 operations. The locations for these commercial burial grounds were selected on the basis of regional requirements for waste disposal. The important physical characteristics of the four sites located in humid areas are summarized in Table 2.1-1. These sites are all in locations of moderately high precipitation with soils of relatively low permeability. These factors have made the control and management of surface and ground water a major operational consideration.

Waste containers are generally buried randomly as received at the eastern sites. The waste containers are protected from contact with rain water through the daily application of earth backfill or through the use of temporary covers such as tarps. Each trench contains a mixture of radionuclides and waste forms. A brief summary of the operating practices at Sheffield, West Valley, Morehead, and Barnwell is given in Table 2.1-2. Covering and sealing filled burial trenches is also used as a water control measure at humid sites. Typically about 1 to 3 m of soil or clay is mounded

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

Characteristic	Sheffield, Illinois	West Valley, New York	Morehead, Kentucky	Barnwell, South Carolina
Licensed Area (ha)	9	9	102	110
Burial Capacity (m^3)	2.0×10^5	2.0×10^5	2.2×10^6	2.4×10^6
Climate	Humid	Humid	Humid	Humid
Mean Annual Precipitation (cm)	90	100	120	110
Geomorphology	Glacial	Glacial	Ridge and Valley (Appalachian)	Coastal Plain
Surface Material	Glacial drift sand, silt and gravel	Glacial drift sand, silt and gravel	Weathered shale, sand and clay	Sand and clay
Thickness (m)	20 - 30	20 - 30	3 - 5	10
Bedrock Classification	Shale, sandstone and coal	Shale	Shale	Clay, sand, and sandstone
Depth to Saturated Ground Water (m)	5 - 20	1 - 20	1 - 2	10 - 20
Nearest Surface Water	Lake at site boundary	Onsite	500 m	Lower Three Run Creek (2 km)
River Flow	Small, perennial	Small, perennial	Small, perennial	Small, perennial
Water Flow Paths from Burial Areas	Pore spaces in till	Shale fractures	Shale fractures	Pore spaces in sand

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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 Used at Eastern LLW Burial Grounds[a]

Practice	Sheffield, Illinois	West Valley, New York	Morehead, Kentucky	Barnwell, South Carolina
Burial Trench Size (m)	150 x 15-18 x 6-8 deep	180-210 x 10 x 6 deep	60-150 x 24 x 6-8 deep	140 x 15 x 5-7 deep
Waste Disposal Procedure	Trench filled to 0.6 m of surface	Trench filled to original grade level	Trench filled to 0.6 m of surface	Trench filled to 1 m of surface
Waste Covering Frequency	Daily	Daily	Daily	Daily
Cover:				
Type	Compacted clay cover; surface seeded	Excavated earth fill; compacted; topsoil added	1 m compacted clay, mounded and seeded	0.6 m of clay plus additional mounded cover
Depth	Minimum 1 m final cover; mounded	Minimum 3 m cover; mounded to 1.5 m above grade	Minimum 1 m cover; mounded to 0.6 m above grade	3 m cover at center, 1.5 m at edge
Provisions for Water	Trench bottom slopes to centerline and one end, ditch filled with broken brick, sump and standpipe	Trenches sloped 2° sump with riser pipe at low end	1° sloped trenches, pit and standpipe at low corner, clay berm around trench	1° sloped trenches, 0.6-1 m sand bottom, sump and standpipe

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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).

and graded over the top of the waste trench (Murphy and Holter 1980, Sec. 3.1.1).

A generic burial ground is used in this study to provide a basis for a comparative analysis. Such a burial ground has been defined for a humid eastern site in a conceptual decommissioning study by Murphy and Holter (1980, Section 7.0). The following key assumptions are made shallow-land burial facilities at for the reference humid site:

- The reference burial ground operates for 20 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 Humid Site

The reference humid site is assumed to be located on an upland area of generally flat terrain as shown in Figure 2.1-1. The near surface geologic materials consist of windblown silt (loess) over glacial till and clay deposits. A summary of the reference humid site characteristics (taken from Section 7.0 of Murphy and Holter 1980) is given in Table 2.1-3.

The reference humid site is assumed to have a continental climate, with a wide temperature range throughout the year. Occasional periods of high temperatures and humidity occur during the summer, while periods of extreme cold and high winds occur during winter. The average annual precipitation is about 90 cm, and occurs mostly as rain during the late spring and summer. Moderate snowfall occurs during December through March. The maximum snowpack occurs during March, and is estimated to equal about 25 cm of water (Murphy and Holter 1980, Section 7.4).

The highest wind speeds occur during the spring, and average about 5 km/hr. In addition, tornadoes were experienced with an incidence of $1.4 \times 10^{-4}/\text{km}^2$-year for the period from 1953 to 1972 (Murphy and Holter 1980, Section 7.4). Surface material at the humid site consists of loess,

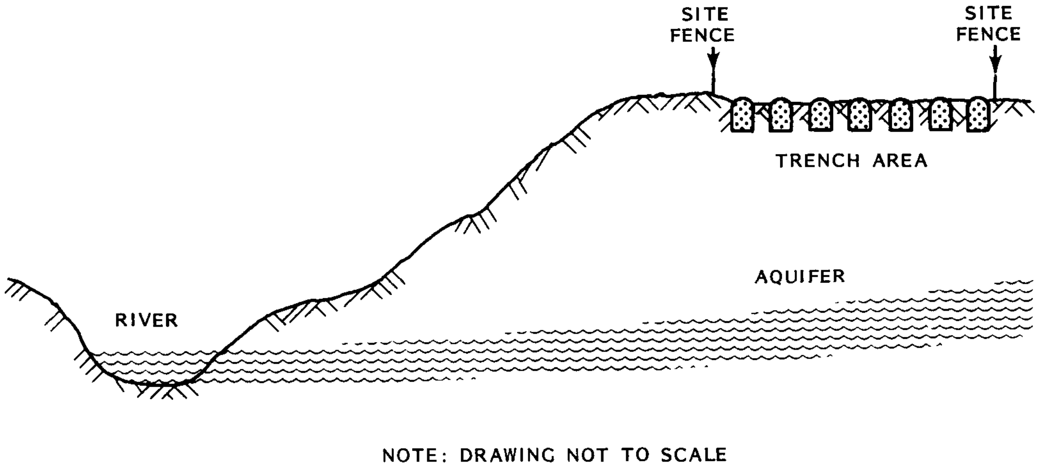

FIGURE 2.1-1. Schematic Cross Section of the Reference Humid LLW Burial Ground Site

till, sand or gravel; bedrock material is composed of shale, limestone or coal.

2.1.2 Reference Trench Information

For consistency within this program, the same reference site design defined for an arid site is used for the humid site with a few modifications (McKenzie et al. 1982, Vol. 2). The plot plan for the reference arid burial

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

Characteristic	Value
Bulk density of surface material	1.7×10^3 kg/m^3
Distance to surface water	1.0 km
Depth to ground water	10 m
Groundwater gradient	5%
Average groundwater velocity	3.7 m/yr

(a) Taken in part from Table 7.4-3 of Murphy and Holter (1980).

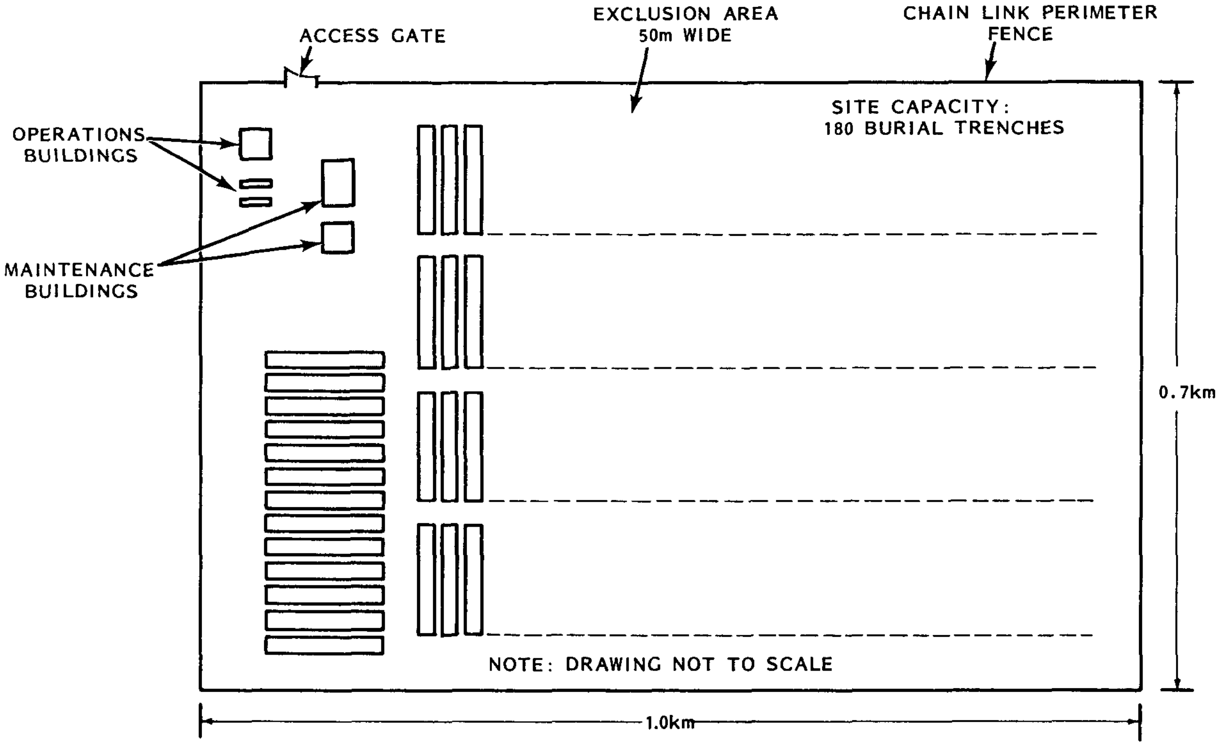

FIGURE 2.1-2. Plot Plan for the Reference Humid Site LLW Burial Ground

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 2.5 x 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 the dimensions and cross sectional design of a reference humid site burial trench. A minimum space of 3 m is assumed between the top edges of adjacent trenches. Figure 2.1-4 shows a cutaway view of the reference humid site trench.

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

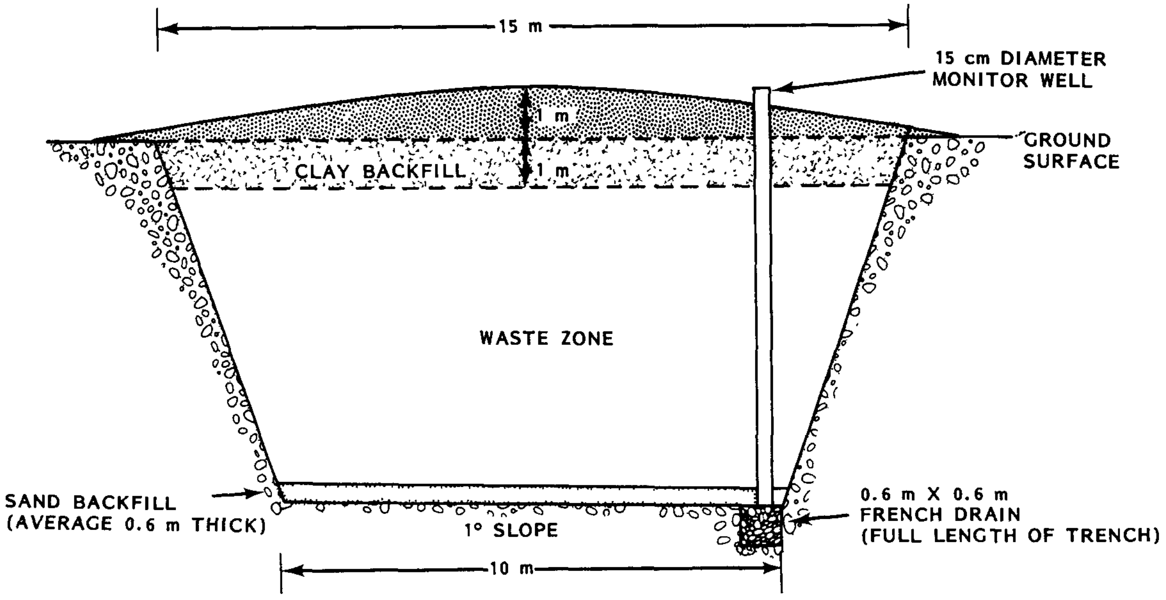

FIGURE 2.1-3. Cross Section View of the Reference Humid Site Trench

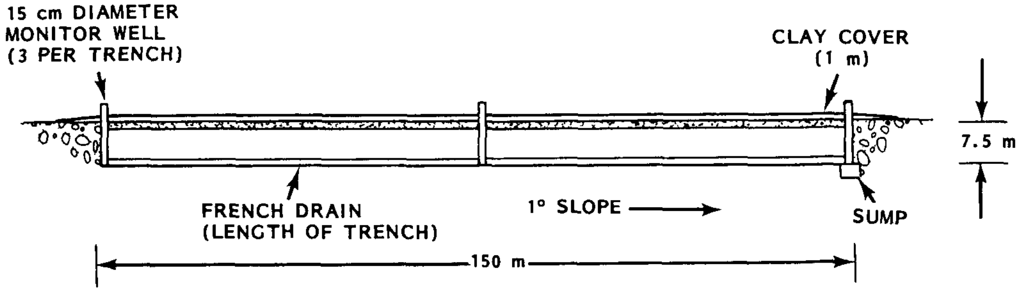

FIGURE 2.1-4. Cutaway View of the Reference Humid Site Trench

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

Site Parameter	Value
Total area	70 ha
Site waste capacity	2.5×10^6 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).

2.2 REFERENCE ENVIRONMENT

The reference environment assumed for the humid site is typical of much of the eastern United States. Annual precipitation ranges from 100 to 125 cm. Summers are warm and humid, while winters are cold. Abundant moisture supports a vigorous plant community that matures to a forest dominated by both deciduous and coniferous trees. Following disturbance, such as construction of a burial ground, initial invading plants are primarily annual weedy forbs. Grasses and shrubs soon replace the forbs, but they, in turn, eventually give way to the trees that dominate the climax forest community. An increasing accumulation of living plant biomass occurs until the self-sustaining forest community is established at 150-200 years. At that point a quantity of plant material equal to the annual plant production is returned to the soil for decomposition and recycling. In addition to the producers (plants), other functional living components include consumers that feed on green plants or animals and the reducer-decomposer organisms, including earthworms, that break down non-living plant and animal remains.

Activities of the animal community include burrow construction by small to medium-sized mammals and some invertebrates. These burrowing animals spend part or most of their time below ground. 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, we believe, realistic 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 between 40 and 200 years by increasing the fraction of plant productivity that is returned annually to the soil and by decreasing the amount tied up in added biomass.

2.3 REFERENCE RADIONUCLIDE INVENTORIES FOR THE HUMID 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). The NRC estimates that about 9.7 x 10^5 m^3 of LLW will be generated in the Southeast. The radionuclides considered by the NRC in each waste stream, radionuclide half-lives, and their principal means of production are listed in Table 2.3-1.

In the DEIS, the NRC further identifies 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 Southeast 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 percent weight solids prior to solidification. All compactible trash waste streams are assumed to be compacted. The net result of these methods is to increase the concentration of radionuclides in the waste.

TABLE 2.3-1. Radionuclides Considered in Humid Eastern Site 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 scintillation 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 4.5 Ci/m^3 for waste spectrum 1 and 5.3 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	1.8E-02(b)	3.4E-04		2.9E-03	4.8E-03	1.6E-03	2.8E-02
C-14	1.4E-03	2.0E-05		2.6E-04	4.2E-04	1.4E-04	2.2E-03
Fe-55	6.3E-01	3.7E-03					6.3E-01
Ni-59	2.2E-03	1.3E-05					2.2E-03
Co-60	1.7E+00	9.8E-03		6.0E-05	6.6E-04	2.3E-04	1.7E+00
Ni-63	1.8E-01	1.1E-03					1.8E-01
Nb-94	6.8E-05	4.0E-07					6.8E-05
Sr-90	3.5E-03	3.7E-05		8.6E-05	3.6E-04	9.4E-05	4.1E-03
Tc-99	7.8E-05	4.2E-07		1.7E-10	5.1E-10	1.7E-10	7.8E-05
I-129	2.2E-04	1.2E-06					2.2E-04
Cs-135	8.0E-05	4.2E-07					8.0E-05
Cs-137	1.8E+00	9.6E-03		1.9E-04	5.7E-04	1.9E-04	1.8E+00
U-235	6.1E-07	1.1E-08	2.1E-05				2.2E-05
U-238	4.8E-07	9.0E-08	1.3E-04				1.3E-04
Np-237	1.2E-10	2.2E-12					1.2E-10
Pu-238	6.0E-04	2.8E-05					6.3E-04
Pu-239/240	5.4E-04	1.5E-05					5.5E-04
Pu-241	1.7E-02	5.1E-04					1.8E-02
Pu-242	1.2E-06	3.3E-08					1.2E-06
Am-241	4.6E-04	1.8E-05		2.0E-07			4.8E-04
Am-243	2.7E-05	1.2E-06					2.8E-05
Cm-243	4.8E-07	2.8E-08					5.1E-07
Cm-244	3.0E-04	2.0E-05					3.2E-04
	4.4E+00	2.5E-02	1.5E-04	3.5E-02	6.8E-03	2.2E-03	4.5E+00

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

(b) Where 1.8E-02 = 1.8×10^{-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	2.2E-02(b)	1.2E-03		8.7E-03	2.4E-03	1.6E-03	3.6E-02
C-14	1.8E-03	7.0E-05		7.6E-04	2.1E-04	1.4E-04	3.0E-03
Fe-55	7.7E-01	1.3E-02					7.8E-01
Ni-59	2.6E-03	4.5E-05					2.6E-03
Co-60	2.0E+00	3.5E-02		1.2E-05	3.3E-04	2.3E-04	2.0E+00
Ni-63	2.1E-01	4.0E-03					2.1E-01
Nb-94	8.3E-05	1.4E-06					8.4E-05
Sr-90	4.3E-03	1.3E-04		2.6E-05	1.8E-04	9.4E-05	4.7E-03
Tc-99	9.7E-05	1.5E-06		5.1E-10	2.6E-10	1.7E-10	9.8E-05
I-129	2.6E-04	4.2E-06					4.2E-06
Cs-135	9.7E-05	1.5E-06					9.8E-05
Cs-137	2.2E+00	3.4E-02		5.7E-04	2.8E-04	1.9E-04	2.2E+00
U-235	7.4E-07	4.1E-08	6.2E-05				6.3E-05
U-238	5.9E-06	3.2E-07	3.8E-04				3.9E-04
Np-237	1.4E-10	2.2E-12					1.4E-10
Pu-238	7.3E-04	1.0E-04					8.3E-04
Pu-239/240	6.5E-04	5.4E-05					7.0E-04
Pu-241	2.1E-02	1.8E-03					2.3E-02
Pu-242	1.4E-06	1.2E-07					1.5E-06
Am-241	5.5E-04	6.3E-05		6.1E-07			6.1E-04
Am-243	3.3E-05	4.3E-06					3.7E-05
Cm-243	5.9E-07	9.9E-08					6.9E-07
Cm-244	3.6E-04	7.3E-05					4.3E-04
	5.2E+00	1.3E-01	4.5E-04	1.0E-02	3.4E-03	2.2E-03	5.3E+00

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

(b) Where 2.2E-02 = 2.2 x 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 humid site, radiation exposure scenarios and the resulting source terms are required. The methods used to develop the exposure scenarios and the source terms are similar to those used in an earlier topical report on a reference low-level site (McKenzie et al. 1982, Vol. 2) in the arid West. 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 maximally 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.

As in the topical report on a reference arid site (McKenzie et al. 1982, Vol. 2), we will compare the intruder-agriculture scenario with the biotic transport scenarios for the reference humid site. The intruder-agriculture scenario relies on the surface soil concentration developed for 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 loss of waste container integrity and degeneration of waste form 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 burial waste containers. Rough estimates of the durability of waste containers buried at humid sites can be made by reviewing information from the literature. Programs have been conducted at U.S. Department of Energy LLW burial sites to assess the feasibility of exhuming, repacking, and relocating buried radioactive material. In one program, a test excavation was made in a burial trench at the Savannah River Laboratory (Horton 1977). The wastes were originally buried in 1958; they were exhumed in 1972. Overburden was removed using a conventional mechanical shovel from a 7.5 m by 9 m section of trench. Waste material was encountered about 2 m below the surface. Materials were removed to a total depth of about 6 m. The excavated waste materials were randomly distributed in the soil. Identified waste items included: wooden burial boxes, steel bars and pipes, electrical wires, ropes, tarpaulins, a variety of plastic and cotton protective clothing articles, rubber shoe covers, cardboard boxes, and miscellaneous paper materials. The waste articles were exceptionally well preserved, and though the material was typically damp, it was not saturated (Horton 1977).

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 Savannah River burial trench. The containers and wastes are assumed to decompose with a 15-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 50-year half-time.

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

The maximally 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 eight hours per day, five 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

3.2.1 Animal Intrusion

Potential animal burrowers considered in this report include the eastern chipmunk (*Tamias striatus*), woodchuck (*Marmota monax*), moles (*Parascalops breweri*, *Scalopus aquaticus*, *Condylura cristata*), ants, and earthworms (Table 3.2-1). Although other burrowing species may be present in the humid East, we believe the above animals are representative of the general burrowing activity and volumes of soil likely to be displaced by animals on a low-level waste burial site.

To estimate the amount of soil moved by chipmunks and woodchucks, we selected a representative value from the literature for animal density and burrow volume (Thomas 1974, Burt and Grossenheider 1976, Henderson and Gilbert 1978). We assumed one animal per burrow and that the entire soil

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

Radionuclide[b]	Waste Spectrum 1[c] 100 years (pCi/m^2)	Waste Spectrum 2[c] 100 years (pCi/m^2)
H-3	8.5E+06[d]	8.9E+06
C-14	1.8E+08	1.8E+08
Fe-55	3.7E-01	3.5E-01
Ni-59	1.8E+08	1.6E+08
Co-60	2.7E+05	2.4E+05
Ni-63	7.2E+09	6.4E+09
Sr-90	2.9E+07	2.6E+07
Tc-99	6.4E+06	6.1E+06
I-129	1.8E+07	1.6E+07
Cs-135	6.6E+06	6.1E+06
Cs-137	1.5E+10	1.4E+10
U-235	1.8E+06	3.9E+06
U-238	1.1E+07	2.4E+07
Np-237	9.9E+00	8.7E+00
Pu-238	2.4E+07	2.4E+07
Pu-239/240	4.4E+07	4.4E+07
Pu-241	1.2E+07	1.2E+07
Pu-242	9.9E+04	9.4E+04
Am-241	7.7E+07	7.4E+07
Am-243	2.3E+06	2.3E+06
Cm-243	3.7E+03	3.8E+03
Cm-244	5.7E+05	5.8E+05

(a) The calculations are performed for 20-year-old decayed wastes after loss of institutional controls 100 years later.

(b) Daughter product ingrowth is not included in this table.

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

(d) Where 8.5E+06 = 8.5 X 10^6.

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

Animal	Percent Distribution of Burrow System Below Ground Depth Interval (m)					Average Density (Animals/ha)	Average Burrow Volume (m^3)	Estimated Volume of Soil Brought to Surface in First Year (m^3/ha)	Preparation of New Burrow Systems/Year
	0 - 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	>2.0				
Chipmunk	60	30	10	0	0	10	0.01	0.1	0.50
Woodchuck	50	30	20	0	0	6	0.15	0.9	0.17
Mole	90	10	0	0	0	10	1.3	6.5	1.00
Ants	70	10	10	5	5	50 (Colonies)	0.002	0.1	0.75
Earthworm	100	0	0	0	0	--	--	0.7	1.00

volume within the burrow system was brought to the surface. Burrowing depths (Table 3.2-1) for chipmunks and woodchucks were based on data from Panuska and Wade (1956) and Burt and Grossenheider (1976), respectively.

Moles and earthworms redistribute a large amount of soil below ground, with only a fraction of that volume actually being moved to the surface. Our estimate of the amount of soil brought to the surface by moles is based on an average burrow system volume calculated from Harvey (1976), a population density from Giger (1973), and an assumption that half the soil displaced by burrowing moles is deposited on the surface. Burrowing depths for moles were based on information from Burt and Grossenheider (1976). Our estimate of the amount of soil moved to the surface by earthworms is based on the soil turnover rate for the top 0.25 m of soil presented in Reichle et al. (1971), the vertical distribution of worms presented in Grant (1956) and Gerard (1967), and an assumption that 1% of the soil displaced by worms actually ends up deposited on the surface.

The burrowing activity and depths for ants on the eastern low-level waste site was assumed to be the same as that on the western site (McKenzie et al. 1982), which was based on data for harvester ants (Pogonomyrmex spp.). One species of harvester ant (Pogonomyrmex badius) does occur in the East (Gentry and Stiritz 1972) along with other ant species (e.g., Dolichoderus taschenbergi and Formica fusca) that construct burrow systems (Creighton 1950, Cline et al. 1982).

Considerable mixing of surface litter and soil results from the belowground burrowing activities of animals, particularly moles and earthworms. This mixing of soil was not accounted for in our modeling efforts; however, the exposure scenario assumed that at year 100 the surface litter and its associated radionuclides would be thoroughly mixed in the upper 0.5 m of soil. The 100 year time frame for mixing the upper 0.5 m of soil and surface litter is reasonable, since this is the soil strata in which moles and earthworms are most active (Table 3.2-1) and earthworm activity alone has been estimated to turn over the upper 0.25 m of soil completely in 44 years (Reichle et al. 1971).

3.2.2 Plant Intrusion

Vegetative cover on the eastern low-level waste site was assumed to have changed, over 200 years, from a bare field to a "climax" (Odum 1959, Whittaker 1970) or "steady state" (Bormann and Likens 1979) plant community dominated by a northern hardwood/oak-hickory forest (Odum 1959, Whittaker 1970, Bormann and Likens 1979). We assumed that early successional plants invaded the site within the first year after cessation of institutional control.

Net aboveground annual vegetative production (gross productivity minus plant respiration) for the first 40 years following the bare field stage was assumed to be 500 g/m^2/yr-dry weight (Whittaker 1970). Net annual production from year 41 on was assumed to be 1,200 g/m^2/yr-dry weight (Whittaker 1970, Lieth 1975).

The apportionment of the net annual production to the above and belowground biomass components was based on a root-to-shoot weight ratio of 0.20 (Santantonio et al. 1977, Harris et al. 1980).

Depending on the successional stage of the plant community, variable proportions of the total (above and belowground components) net annual production goes into the formation of (1) woody supportive tissues, including roots (standing crop biomass) and (2) litter that falls to the ground or roots that die. We assumed, for simplicity, that during the first 40 years, 40% of the total net annual production would go into standing crop biomass. The remaining 60% would be litter that falls to the ground and roots that die (Whittaker et al. 1974). From year 41 to year 200 (climax), a linearly decreasing rate of the total net annual production was estimated to go into standing crop biomass. Following climax, a quantity of biomass equal to total net annual production was assumed to go into litter and dying roots. It was assumed that any radionuclides translocated to the above and belowground plant parts were distributed to the standing crop biomass and litter (including dying roots) in the proportions presented above.

The root biomass vertical distribution profile for all developmental stages of the plant community was based primarily on information from Kochenderfer (1973), with supportive data from Whittaker and Woodwell (1969), Leaf et al. (1971), Van Hook et al. (1977), and Kimmins and Hawkes (1978). Sixty percent of the root biomass (both the standing crop and the roots that die each year) was assumed to occur between the soil surface and 0.5 m deep; 30%, between 0.5 and 1.0 m; 7%, between 1.0 and 1.5 m; 2%, between 1.5 and 2.0 m; and 1%, deeper than 2 m.

Conversion from dry to wet weight biomass was based on the assumption that 85% of a plant is water (Turner and Kramer 1980). Radionuclide concentration ratios (Table 3.2-2) were then applied to wet weight biomass to calculate radionuclide content of the plants that penetrated the buried wastes. These concentration ratios were the same as used in the FOOD computer program for calculating dose to man from agricultural food products (Napier et al. 1980). These values were assumed for native plant species because data for native plants were lacking.

3.2.3 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 of McKenzie et al. (1982, Vol. 2). Biological components are plant roots, which absorb radionuclides and translocate them to other plant organs (i.e., 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

TABLE 3.2-2. Plant Concentration Ratios for Radionuclides

Radionuclide	Concentration Ratio	Radionuclide	Concentration Ratio
H-3	0.00E+00(a)	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		

(a) Where 0.00E+00 = 0×10^0

each stratum, when present; 2) computes, for each radionuclide in each soil stratum, a new concentration based on plant uptake and radionuclide redistribution; 3) determines the amount (m^3/ha) of soil brought to the surface from the various strata by animal activity; and 4) computes, for each radionuclide in each stratum, a new concentration based on soil movement. After the first year, the soil moved by the animals is contaminated from 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 aboveground plant parts based on annual biomass production and the root to shoot ratio. The belowground portion of radioactivity is distributed in the cover profile in proportion to the root biomass in each of three 0.5 m-thick strata above the waste zone. Annual biomass production is assumed to recycle each year; thus, radioactive material is added to each soil stratum by roots and to the soil surface from aboveground plant parts.

3.2.4 Source Terms

The source terms resulting from intrusion and active biotic transport processes for waste spectra 1 and 2 at the humid site are shown in Table 3.2-3. These concentrations are assumed to accumulate gradually during 100 years of institutional control (with no corrective action taken by waste site management) and over longer time periods until the peak surface radionuclide concentrations are reached. For waste spectrum 1, the peak concentration (in pCi/m^3) occurs about 240 years after site closure. For waste spectrum 2, the peak concentration occurs about 270 years after site closure. The concentrations are shown for 100 years after site closure for comparison with the human intrusion scenario, and for the peak concentration year as a determination of the long-term potential of biotic transport processes.

The maximally 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 humid 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 eight hours a day five days 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.

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 four soil depths over a 500 year time span. The surface accumulation of about 3.3 Ci/ha of trench surface occurs at 100 years after site closure. The peak concentration in the trench surface soil is about 4.7 Ci/ha, and it occurs 237 years after site closure. The quantities shown in Figure 3.2-1 are corrected for radioactive decay and daughter product ingrowth with the assumed 15-year container decomposition half-time.

Figure 3.2-2 shows the total Ci/ha present at four soil depths for waste spectrum 2 over a 500 year time span. The accumulated concentration at the surface 100 years after site closure is about 2.5 Ci/ha. The peak surface concentration, 4.7 Ci/ha, occurs about 266 years after site closure.

TABLE 3.2-3. Surface Soil Concentrations Resulting from Intrusion and Active Transport Processes at the Reference Humid Site

	Waste Spectrum 1(a)		Waste Spectrum 2(a)	
Radionuclides(b)	100 years (pCi/m^2)	237 years (pCi/m^2)	100 years (pCi/m^2)	266 years (pCi/m^2)
H-3	7.1E+03(c)	8.1E+00	5.9E+03	1.9E+00
C-14	1.3E+05	3.5E+05	1.0E+05	4.3E+05
Fe-55	4.9E-04	--(d)	3.6E+04	--(d)
Ni-59	5.9E+06	3.0E+07	4.2E+06	3.7E+07
Co-60	4.4E+03	3.2E-04	3.1E+03	--(d)
Ni-63	2.3E+08	4.5E+08	1.7E+08	4.5E+08
Sr-90	9.9E+06	1.8E+06	6.9E+06	1.1E+06
Tc-99	2.7E+06	1.4E+07	2.1E+06	1.8E+07
I-129	6.2E+05	3.2E+06	4.5E+05	4.0E+06
Cs-135	2.7E+04	1.3E+05	2.0E+04	1.6E+05
Cs-137	6.0E+07	1.2E+07	4.5E+07	8.0E+06
U-235	8.9E+03	4.3E+04	1.5E+04	1.3E+05
U-238	5.3E+04	2.5E+05	9.6E+04	7.9E+05
Np-237	4.8E-02	2.3E-01	3.4E-02	2.8E-01
Pu-238	2.7E+04	3.3E+04	2.1E+04	3.4E+04
Pu-239/240	5.0E+04	1.8E+05	1.9E+04	2.3E+05
Pu-241	1.4E+04	6.9E+01	3.0E+00	2.1E+01
Pu-242	1.1E+02	4.1E+02	8.4E+01	5.0E+02
Am-241	8.7E+04	2.6E+05	6.6E+04	3.1E+05
Am-243	2.6E+03	9.3E+03	2.0E+03	1.2E+04
Cm-243	1.8E+01	3.1E+00	1.5E+01	2.2E+00
Cm-244	2.8E+03	7.2E+01	2.3E+03	3.3E+01

(a) The calculations are performed for 20 year decayed waste after the loss of institutional controls 100 years later, and at the time of peak concentration shown for each waste spectrum. The resulting concentrations are assumed to be mixed in the top 0.5 m of soil.

(b) Daughter product ingrowth is not included in this table.

(c) Where 7.1E+03 = 7.1 X 10^3.

(d) -- indicates a concentration less than 1 x 10^{-7} pCi/m^2.

Again, the quantities shown in Figure 3.2-2 have been corrected for radioactive decay and daughter product ingrowth, with the assumed 50-year container decomposition half-time.

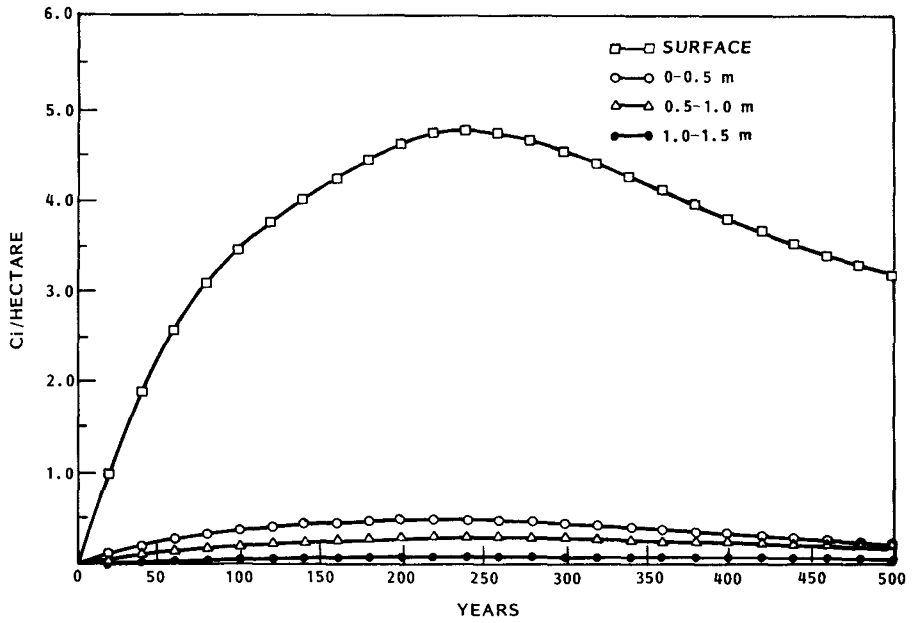

FIGURE 3.2-1. Total Ci/ha Present over 500 Years for Waste Spectrum 1

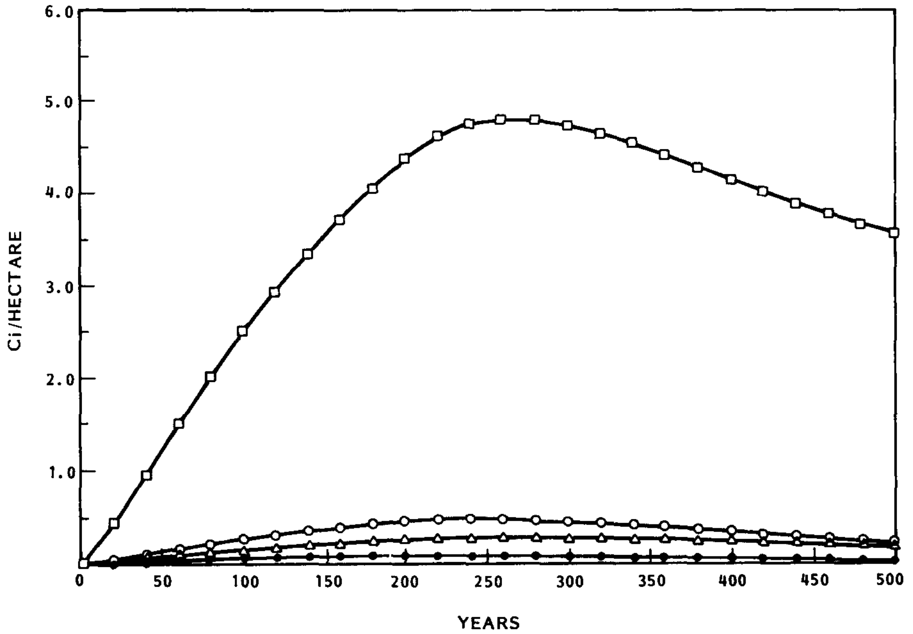

FIGURE 3.2-2. Total Ci/ha Present Over 500 Years for Waste Spectrum 2

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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 models for the source terms defined in Tables 3.1-1 and 3.2-2, 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 inhalation 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:

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

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

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

$R_{j,k}$ = the radiation dose equivalent commitment to the organ of reference from intake (internal exposure pathways) in the previous year j, to year k, 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 THE HUMAN INTRUSION SCENARIO

Doses to the maximally 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 maximally 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 eight hours per day, five 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 largest organ dose is to bone, where a small dose contribution from Sr-90 occurs. The maximum annual dose to bone peaks in the second year of continuous exposure, reaching peak values of 42 rem for waste spectrum 1 and 39 rem for waste spectrum 2. A complete listing of the maximum annual doses for each organ by radionuclide is given in the Appendix.

4.3 BIOLOGICAL INTRUSION AND ACTIVE BIOTIC TRANSPORT DOSE CALCULATIONS

Doses to the maximally 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 3.2-3 for waste spectra 1 and 2. The maximally exposed individual residing on a site contaminated under the biological intrusion and active biotic transport scenario is exposed by inhalation of resuspended radionuclides, ingestion of garden and farm crops grown in the soil, and direct exposure to penetrating radiation. The entire individual's diet, including eggs and meat products, is assumed to be grown

TABLE 4.1-1. Parameters Used for Calculating 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 Maximally Exposed Individual from the Intruder-Agriculture Scenario at the Reference Humid Site[(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	41
	2	Bone	Cs-137 + D	External	42
	1	Lungs	Cs-137 + D	External	41
	1	Thyroid	Cs-137 + D	External	41
	1	GI-LLI	Cs-137 + D	External	41
2[(e)] (Future Wastes)	2	Total body	Cs-137 + D	External	39
	2	Bone	Cs-137 + D	External	39
	1	Lungs	Cs-137 + D	External	38
	2	Thyroid	Cs-137 + D	External	38
	1	GI-LLI	Cs-137 + D	External	38

(a) The doses are calculated over a 50-year continuous exposure period for the waste spectra shown in Tables 3.1-1 and 3.2-3 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 in the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 15-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 for the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 50-year container decomposition half-time.

in or on contaminated soil. The individual is assumed to inhale dust with a concentration of 2 x 10^{-6} g/m^3 for eight hours per day, five 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 maximally exposed individual.

The resulting maximum annual doses and the year during continuous exposure in which the doses peak are given in Tables 4.3-1 and 4.3-2. Table 4.3-1 contains the doses resulting from the mixtures of radionuclides present in the top 0.5 m of trench cover 100 years after site closure. The doses calculated at 100 years after site closure are for comparison with the doses calculated for the intruder-agriculture scenario after loss of institutional controls is assumed to occur (Section 4.2). 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. Doses to the remaining organs are generally controlled by direct exposure to Cs-137 and its daughter Ba-137m. The exception is thyroid, where dose is controlled by ingestion of I-129. The critical organ (or the organ receiving the largest dose) for both waste spectra is bone. Calculated maximum annual doses to bone are 26 rem for waste spectrum 1 and 18 rem for waste spectrum 2.

Doses to the maximally exposed individual resulting from continuous exposure at the time of the peak surface soil concentration are shown in Table 4.3-2. These doses are included to illustrate further the dependence of the calculated doses on the mixture of radionuclides present. Although the total concentrations of radionuclides in the top 0.5 m of soil are at their maximum, the resulting organ doses are generally less than the organ doses calculated for 100 years after site closure. The exception is the dose to thyroid, controlled by the long-lived I-129, which increases. This example calculation indicates that the organ doses reach maximum values at different times than the total surface concentration of the mixtures because of the changing concentrations of individual radionuclides in the mixture.

To illustrate this complex behavior further, we next calculated the organ dose versus time (for total body, bone, and thyroid), and plotted the results for waste spectra 1 and 2. In addition, we plotted the corresponding total concentration of radionuclides in the top 0.5 m of soil. The resulting figures are included here as Figures 4.3-1 and 4.3-2. These figures clearly indicate that the organ doses, controlled by single radionuclides within the mixture, peak at times different than the peak total concentrations. The concentrations of specific radionuclides within the total mixture change with time as a function of their radiological half-lives and biological transport properties. Thus, to determine the relative impacts of biotic transport, it is necessary to compare radiation doses, and not total surface soil concentrations.

TABLE 4.3-1. Maximum Annual Doses to the Maximally Exposed Individual from the Biological Intrusion and Active Biotic Transport Scenario 100 Years after Closure of the Reference Humid Site[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	6.3
	32	Bone	Sr-90 + D	Ingestion	26
	1	Lungs	Cs-137 + D	External	0.18
	3	Thyroid	Cs-137 + D	External	0.52
	1	GI-LLI	Cs-137 + D	External	0.17
2[e] (Future Wastes)	30	Total body	Sr-90 + D	Ingestion	4.4
	32	Bone	Sr-90 + D	Ingestion	18
	1	Lungs	Cs-137 + D	External	0.13
	3	Thyroid	I-129	Ingestion	0.38
	1	GI-LLI	Cs-137 + D	External	0.13

(a) The doses are calculated over a 50-year continuous exposure period for the waste spectra shown in Tables 3.1-1 and 3.2-3.

(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 in the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 15-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 in the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 50-year container decomposition half-time.

TABLE 4.3-2. Maximum Annual Doses to the Maximally Exposed Individual from the Biological Intrusion and Active Biotic Transport Scenario, Beginning the Year that the Surface Soil Concentration Peaks after Closure of the Reference Humid Site(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	1.2
	29	Bone	Sr-90 + D	Ingestion	7.5
	6	Lungs	Cs-137 + D	External	0.051
	4	Thyroid	I-129	Ingestion	1.9
	1	GI-LLI	Cs-137 + D	External	0.035
2(e) (Future Wastes)	29	Total body	Sr-90 + D	Ingestion	0.81
	26	Bone	Ni-63	Ingestion	5.8
	7	Lungs	Cs-137 + D	External	0.048
	4	Thyroid	I-129	Ingestion	2.9
	1	GI-LLI	Cs-137 + D	External	0.023

(a) The doses are calculated over a 50-year continuous exposure period for the waste spectra shown in Tables 3.1-1 and 3.2-3 starting 237 years after site closure for waste spectrum 1 and 266 years after site closure for waste spectrum 2.

(b) The year in which the maximum annual dose occurs during the 50-year continuous exposure period.

(c) Waste Spectrum 1 was based on the current mixture and specific activity of LLW radionuclides in the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 15-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 in the Southeast (U.S. Nuclear Regulatory Commission 1981), with an assumed 50-year container decomposition half-time.

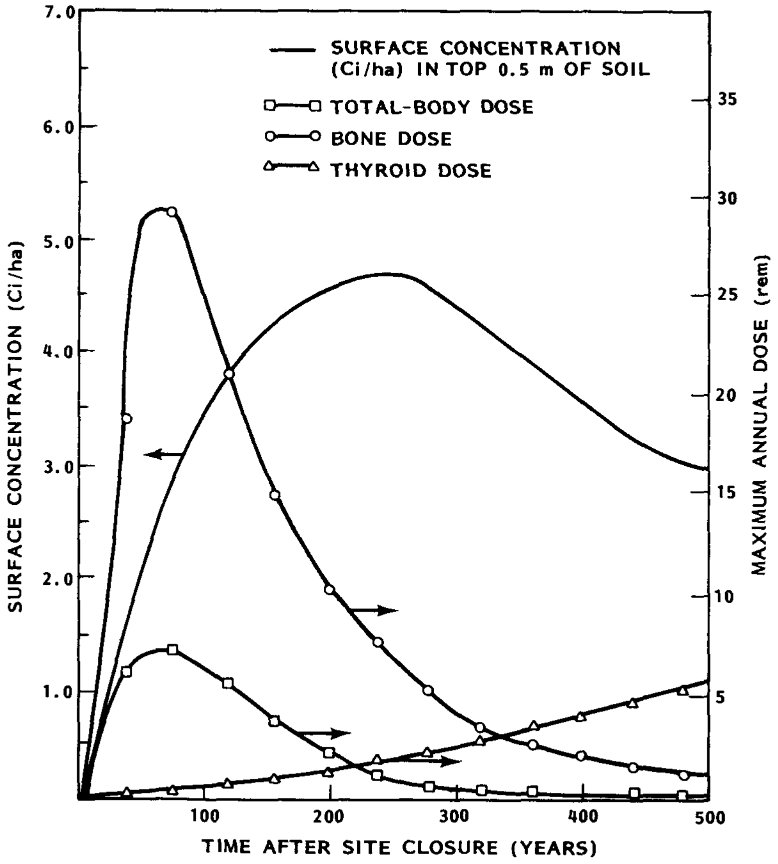

FIGURE 4.3-1. Comparison of Surface Concentration and Organ Dose over 500 Years of Biotic Transport for Waste Spectrum 1

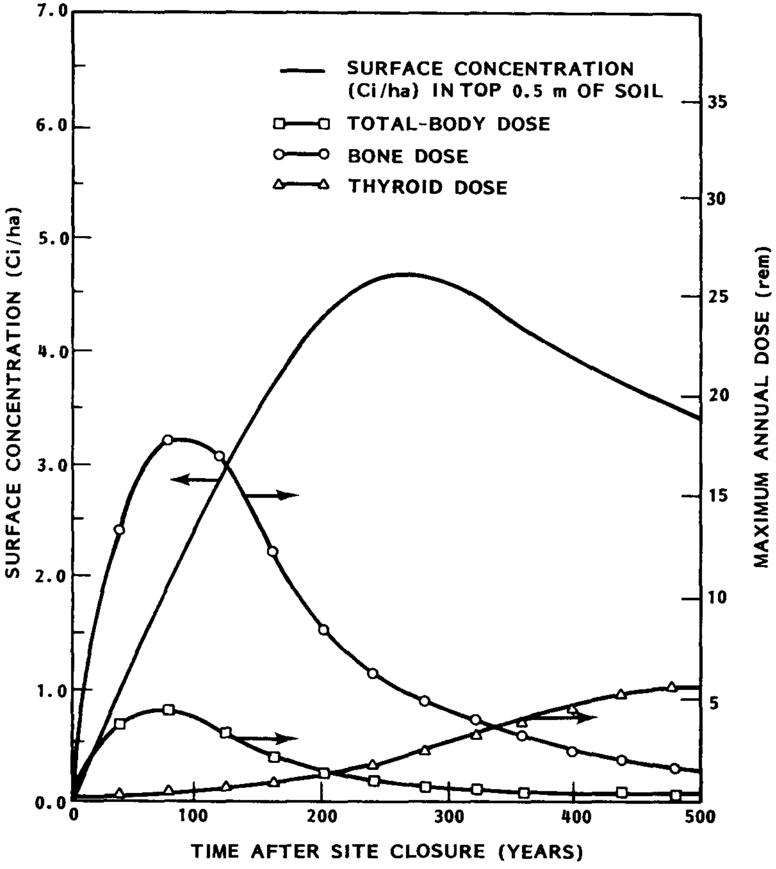

FIGURE 4.3-2. Comparison of Surface Concentration and Organ Dose over 500 Years of Biotic Transport for Waste Spectrum 2

TABLE 4.4-1. Results Comparison for Human Intrusion and Biological Intrusion and Active Biotic Transport for the Reference Humid Site[a]

	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	42	Bone	26	0.62
2	Total Body	39	Bone	18	0.46

(a) Doses for both scenarios are calculated for 100 years after site closure.

4.4 COMPARISON OF RESULTS

A comparison of the maximum annual dose results for the human intrusion and biotic transport scenarios 100 years after closure of the reference humid site 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 parameter values used. For waste spectrum 1, the ratio of the critical organ doses for the biotic transport scenario to the human intrusion scenario is 0.62. For waste spectrum 2, the critical organ ratio (biotic transport to human intrusion) is 0.46. These results indicate that for the reference humid site, the dose resulting from biotic transport may be within a factor of two of the dose resulting from human intrusion. Since the human intrusion doses are controlled by direct exposure to contaminated ground, the peak human intruder dose results at the time of loss of institutional controls, or 100 years after closure of the site. From Figure 4.3-1, the peak biotic transport dose for waste spectrum 1 (to the critical organ, bone) occurs in about year 70 and is about 29 rem. Thus, the ratio of the peak biotic transport dose to the peak human intrusion dose is about 0.7.

The doses calculated for the human intrusion scenario were based on the waste spectra for the Southeast 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 39 rem for this study, from Table 4.4-1, indicates that the two approaches produce similar results.

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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 a biological 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 contaminated food grown at the site, while only 60 kg/yr of contaminated garden crops was available from onsite production in 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 humid 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 15 and 50 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 humid 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. Alternately, if substantial erosion occurs, perhaps as accelerated by the action of burrowing animals, the result may be an increase in the dose to an intruder residing over the burial trench. 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 concerning loss of institutional controls. Alternative time spans may alter the relative importance of the two scenarios.

We are satisfied that the structure of the model for biological 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 an eastern 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 humid East.

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. These results are similar to those reported for an arid western site by McKenzie et al. (1982).

5.1 REFERENCES

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APPENDIX

TABULATION OF MAXIMUM ANNUAL DOSES

TABULATION OF MAXIMUM ANNUAL DOSES

Maximum annual doses to the organs of the maximally 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 15-year half-time was assumed for past wastes in waste spectrum 1, and a 50-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 for the human intrusion scenario in Table A.1, and for the intrusion and active biotic transport scenarios in Tables A.2 and A.3. In Tables A.1 and A.2, the calculations were performed beginning 100 years after site closure to account for an institutional control period. In Table A.3, the calculations were performed beginning the year that the surface soil concentration peaks after closure of the reference humid site. While the 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 A.1, A.2, and A.3. The year in which the maximum annual dose occurs after the start of continuous exposure was reported for each organ. During the dose calculation 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 A.1. Doses by Radionuclide to the Organs of the Maximally 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 (1/2)	Sr-90[c]	6.9×10^{-2}	3.6×10^{-8}	7.4×10^{-4}	6.9×10^{-2}	1.8×10^{-1}	9.4×10^{-8}	6.5×10^{-4}	1.8×10^{-1}
	Cs-137[c]	3.4×10^{-1}	4.9×10^{-6}	4.1×10^{1}	4.1×10^{1}	5.0×10^{-1}	6.1×10^{-6}	3.8×10^{1}	3.8×10^{1}
	Pu-238	3.7×10^{-7}	1.8×10^{-8}	8.9×10^{-7}	1.3×10^{-6}	1.1×10^{-6}	7.9×10^{-8}	8.9×10^{-7}	2.0×10^{-6}
	Pu-240	3.1×10^{-7}	1.5×10^{-8}	7.6×10^{-7}	1.1×10^{-6}	9.4×10^{-7}	6.8×10^{-8}	7.6×10^{-7}	1.8×10^{-6}
	Pu-239	3.1×10^{-7}	1.5×10^{-8}	7.9×10^{-7}	1.1×10^{-6}	9.4×10^{-7}	6.8×10^{-8}	7.9×10^{-7}	1.8×10^{-6}
	Am-241	3.9×10^{-6}	5.7×10^{-8}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-5}	2.4×10^{-7}	1.1×10^{-3}	1.1×10^{-3}
	Totals	4.1×10^{-1}	5.0×10^{-6}	4.1×10^{1}	4.1×10^{1}	6.8×10^{-1}	6.6×10^{-6}	3.8×10^{1}	3.9×10^{1}
Bone (2/2)	Sr-90[d]	7.3×10^{-1}	4.1×10^{-7}	7.2×10^{-4}	7.3×10^{-1}	6.6×10^{-1}	3.8×10^{-7}	6.4×10^{-4}	6.6×10^{-1}
	Cs-137[d]	5.8×10^{-1}	1.1×10^{-5}	4.1×10^{1}	4.1×10^{1}	5.5×10^{-1}	1.1×10^{-5}	3.8×10^{1}	3.8×10^{1}
	Pu-238	2.4×10^{-5}	1.7×10^{-6}	8.9×10^{-7}	2.6×10^{-5}	2.4×10^{-5}	1.7×10^{-6}	8.9×10^{-7}	2.6×10^{-5}
	Pu-240	2.1×10^{-5}	1.5×10^{-6}	7.6×10^{-7}	2.3×10^{-5}	2.1×10^{-5}	1.5×10^{-6}	7.6×10^{-7}	2.3×10^{-5}
	Pu-239	2.1×10^{-5}	1.6×10^{-6}	7.9×10^{-7}	2.3×10^{-5}	2.1×10^{-5}	1.6×10^{-6}	7.9×10^{-7}	2.3×10^{-5}
	Am-241	2.6×10^{-4}	5.6×10^{-6}	1.1×10^{-3}	1.4×10^{-3}	2.5×10^{-4}	5.4×10^{-6}	1.1×10^{-3}	1.4×10^{-3}
	Totals	1.3	2.3×10^{-5}	4.1×10^{1}	4.2×10^{1}	1.2	2.2×10^{-5}	3.8×10^{1}	3.9×10^{1}
Lungs (1/1)	Cs-137[c]	5.5×10^{-2}	1.9×10^{-6}	4.1×10^{1}	4.1×10^{1}	5.1×10^{-2}	1.8×10^{-6}	3.8×10^{1}	3.8×10^{1}
	U-235[c]	—[d]	2.8×10^{-6}	—	2.8×10^{-6}	—	6.1×10^{-6}	—	6.1×10^{-6}
	Pu-238	—	4.6×10^{-5}	8.9×10^{-7}	4.7×10^{-5}	—	4.6×10^{-5}	8.9×10^{-7}	4.7×10^{-5}
	Pu-240	—	3.9×10^{-5}	7.6×10^{-7}	4.0×10^{-5}	—	3.9×10^{-5}	7.6×10^{-7}	4.0×10^{-5}
	Am-243	—	4.2×10^{-6}	—	4.2×10^{-6}	—	4.2×10^{-6}	—	4.2×10^{-6}
	Pu-239	—	3.9×10^{-5}	7.9×10^{-7}	4.0×10^{-5}	—	3.9×10^{-5}	7.9×10^{-7}	4.0×10^{-5}
	Am-241	—	1.5×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	—	1.4×10^{-4}	1.1×10^{-3}	1.2×10^{-3}
	Totals	5.5×10^{-2}	2.8×10^{-4}	4.1×10^{1}	4.1×10^{1}	5.1×10^{-2}	2.8×10^{-4}	3.8×10^{1}	3.8×10^{1}
Thyroid (1/2)	I-129	4.4×10^{-1}	1.0×10^{-6}	1.0×10^{-4}	4.4×10^{-1}	6.0×10^{-1}	1.6×10^{-6}	8.9×10^{-5}	6.0×10^{-1}
	Cs-137[c]	—	—	4.1×10^{1}	4.1×10^{1}	—	—	3.8×10^{1}	3.8×10^{1}
	Totals	4.4×10^{-1}	1.0×10^{-6}	4.1×10^{1}	4.1×10^{1}	6.0×10^{-1}	1.6×10^{-6}	3.8×10^{1}	3.8×10^{1}
GI-LLI (1/1)	Sr-90[c]	1.2×10^{-1}	9.5×10^{-9}	7.4×10^{-4}	1.2×10^{-1}	1.1×10^{-1}	8.5×10^{-9}	6.7×10^{-4}	1.1×10^{-1}
	Cs-137[c]	1.9×10^{-2}	9.1×10^{-8}	4.1×10^{1}	4.1×10^{1}	1.7×10^{-2}	8.5×10^{-8}	3.8×10^{1}	3.8×10^{1}
	U-235[c]	1.0×10^{-4}	1.1×10^{-9}	—	1.0×10^{-4}	2.3×10^{-4}	2.5×10^{-9}	—	2.3×10^{-4}
	Th-234	—	1.1×10^{-8}	—	1.1×10^{-8}	—	2.3×10^{-8}	—	2.3×10^{-8}
	Pu-238	1.3×10^{-4}	1.5×10^{-8}	8.9×10^{-7}	1.3×10^{-4}	1.3×10^{-4}	1.5×10^{-8}	8.9×10^{-7}	1.3×10^{-4}
	Pu-240	1.1×10^{-4}	1.3×10^{-8}	7.6×10^{-7}	1.1×10^{-4}	1.1×10^{-4}	1.3×10^{-8}	7.6×10^{-7}	1.1×10^{-4}
	Pu-239	1.1×10^{-4}	1.3×10^{-8}	7.9×10^{-7}	1.1×10^{-4}	1.1×10^{-4}	1.3×10^{-8}	7.9×10^{-7}	1.1×10^{-4}
	Am-241	4.3×10^{-4}	5.0×10^{-8}	1.1×10^{-3}	1.6×10^{-3}	—	4.8×10^{-8}	1.1×10^{-3}	1.1×10^{-3}
	Totals	1.4×10^{-1}	2.1×10^{-7}	4.1×10^{1}	4.1×10^{1}	1.3×10^{-1}	2.1×10^{-7}	3.8×10^{1}	3.8×10^{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) Short-lived daughters are included

(d) Dashes indicate a dose contribution of less than 1 x 10^9 rem

TABLE A.2. Doses by Radionuclide to the Organs of the Maximally Exposed Individual Resulting from the Intrusion/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 (30/30)	Sr-90[c]	6.2	1.3×10^{-3}	1.3×10^{-4}	6.2	4.3	9.3×10^{-4}	8.7×10^{-5}	4.3
	Cs-137[c]	1.7×10^{-2}	6.7×10^{-5}	8.5×10^{-2}	1.0×10^{-1}	1.3×10^{-2}	5.0×10^{-5}	6.4×10^{-2}	7.7×10^{-2}
	Pu-238	2.1×10^{-7}	3.0×10^{-5}	—[d]	3.0×10^{-5}	1.6×10^{-7}	2.4×10^{-5}	—	2.4×10^{-5}
	Pu-240	2.2×10^{-7}	3.3×10^{-5}	—	3.3×10^{-5}	1.7×10^{-7}	2.5×10^{-5}	—	2.5×10^{-5}
	Pu-239	2.2×10^{-7}	3.3×10^{-5}	—	3.3×10^{-5}	1.7×10^{-7}	2.5×10^{-5}	—	2.5×10^{-5}
	Am-241	2.4×10^{-6}	1.1×10^{-4}	1.2×10^{-6}	1.1×10^{-4}	1.8×10^{-6}	8.0×10^{-5}	9.2×10^{-7}	8.2×10^{-5}
	Totals	6.2	1.6×10^{-3}	$8.5 \times 10^{-}$	6.3	4.3	1.1×10^{-3}	6.4×10^{-2}	4.4
Bone (32/32)	Ni-63	1.5	—	—	1.5	1.1	—	—	1.1
	Sr-90[c]	2.5×10^{1}	5.4×10^{-3}	1.2×10^{-4}	2.5×10^{1}	1.7×10^{1}	3.8×10^{-3}	1.2×10^{-6}	1.7×10^{1}
	Cs-137[c]	$1.9 \times 10^{-}$	1.2×10^{-4}	$8.1 \times 10^{-}$	$8.1 \times 10^{-}$	1.4×10^{-2}	9.1×10^{-5}	6.1×10^{-2}	7.5×10^{-2}
	Pu-238	4.6×10^{-6}	6.9×10^{-4}	—	6.9×10^{-4}	3.6×10^{-6}	5.3×10^{-4}	—	5.3×10^{-4}
	Pu-240	5.2×10^{-6}	7.8×10^{-4}	—	7.8×10^{-4}	4.0×10^{-6}	5.9×10^{-4}	—	5.9×10^{-4}
	Pu-239	5.2×10^{-6}	7.8×10^{-4}	—	7.8×10^{-4}	4.0×10^{-6}	5.9×10^{-4}	—	5.9×10^{-4}
	Am-241	6.0×10^{-5}	2.7×10^{-3}	1.2×10^{-6}	2.8×10^{-3}	4.5×10^{-5}	2.0×10^{-3}	9.2×10^{-7}	2.0×10^{-3}
	Totals	2.6×10^{1}	$1.1 \times 10^{-}$	$8.1 \times 10^{-}$	2.6×10^{1}	1.8×10^{1}	7.7×10^{-3}	6.1×10^{-2}	1.8×10^{1}
Lungs (1/1)	Sr-90	—	2.3×10^{-5}	2.5×10^{-4}	2.7×10^{-4}	—	1.6×10^{-5}	1.7×10^{-4}	1.9×10^{-4}
	Tc-99	3.9×10^{-5}	—	—	3.9×10^{-5}	3.0×10^{-5}	—	—	3.0×10^{-5}
	Cs-137[c]	3.2×10^{-3}	$3.8 \times 10^{-}$	$1.7 \times 10^{-}$	1.7×10^{-1}	2.4×10^{-3}	—	1.3×10^{-1}	1.3×10^{-1}
	U-235	—	$6.8 \times 10^{-}$	—	$6.8 \times 10^{-}$	—	1.1×10^{-4}	—	1.1×10^{-4}
	Pu-238	1.8×10^{-7}	2.5×10^{-4}	1.0×10^{-9}	2.5×10^{-4}	$1.4 \times 10^{-}$	2.0×10^{-4}	—	2.0×10^{-4}
	Cm-244	—	2.7×10^{-5}	—	2.7×10^{-5}	—	2.2×10^{-5}	—	2.2×10^{-5}
	Pu-240	$1.6 \times 10^{-}$	2.2×10^{-4}	—	2.2×10^{-4}	1.2×10^{-7}	1.6×10^{-4}	—	1.6×10^{-4}
	Am-243	—	2.3×10^{-5}	—	2.3×10^{-5}	—	1.8×10^{-5}	—	1.8×10^{-5}
	Pu-239	1.6×10^{-7}	2.2×10^{-4}	—	2.2×10^{-4}	1.2×10^{-7}	1.6×10^{-4}	—	1.6×10^{-4}
	Am-241	$5.8 \times 10^{-}$	8.1×10^{-4}	1.3×10^{-6}	8.1×10^{-4}	4.4×10^{-7}	6.2×10^{-4}	9.7×10^{-7}	6.2×10^{-4}
	Totals	3.2×10^{-3}	1.7×10^{-3}	$1.7 \times 10^{-}$	1.7×10^{-1}	2.4×10^{-3}	1.3×10^{-3}	1.3×10^{-1}	1.3×10^{-1}
Thyroid (3/3)	I-129	3.5×10^{-1}	3.2×10^{-4}	3.5×10^{-6}	3.5×10^{-1}	2.6×10^{-1}	2.3×10^{-4}	2.5×10^{-6}	2.6×10^{-1}
	Cs-137	—	—	1.6×10^{-1}	1.6×10^{-1}	—	—	1.2×10^{-1}	1.2×10^{-1}
	Totals	3.5×10^{-1}	3.2×10^{-4}	1.6×10^{-1}	5.1×10^{-1}	2.6×10^{-1}	2.3×10^{-4}	1.2×10^{-1}	3.8×10^{-1}
GI-LLI (1/1)	Sr-90[c]	—	$1.5 \times 10^{-}$	2.5×10^{-4}	2.6×10^{-4}	—	1.0×10^{-5}	1.7×10^{-4}	1.8×10^{-4}
	Cs-137	—	1.8×10^{-6}	1.7×10^{-1}	1.7×10^{-1}	—	1.3×10^{-6}	1.3×10^{-1}	1.3×10^{-1}
	U-235	6.1×10^{-6}	2.8×10^{-8}	—	6.1×10^{-6}	1.0×10^{-5}	4.8×10^{-8}	—	1.0×10^{-5}
	Th-234	—	$2.5 \times 10^{-}$	—	2.5×10^{-7}	—	4.6×10^{-7}	—	4.6×10^{-7}
	Pu-238	1.7×10^{-6}	8.4×10^{-8}	1.0×10^{-9}	1.7×10^{-6}	1.3×10^{-6}	6.5×10^{-8}	—	1.3×10^{-6}
	Pu-240	1.4×10^{-6}	7.3×10^{-8}	—	1.4×10^{-6}	1.1×10^{-6}	5.6×10^{-8}	—	1.2×10^{-6}
	Pu-239	1.4×10^{-6}	7.3×10^{-8}	—	1.4×10^{-6}	1.1×10^{-6}	5.6×10^{-8}	—	1.2×10^{-6}
	Am-241	5.5×10^{-6}	2.7×10^{-7}	1.3×10^{-6}	6.8×10^{-1}	4.1×10^{-6}	2.1×10^{-7}	9.7×10^{-7}	5.3×10^{-6}
	Totals	1.6×10^{-5}	1.8×10^{-5}	1.7×10^{-1}	1.7×10^{-1}	1.8×10^{-5}	1.3×10^{-5}	1.3×10^{-1}	1.3×10^{-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) Short-lived daughters are included

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

TABLE A.3. Doses by Radionuclide to the Organs of the Maximally Exposed Individual Resulting from the Intrusion/Active Biotic Transport Scenario, Beginning the Year that the Surface Soil Concentration Peaks after Closure of the Reference Humid Site

		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 (30/29)	Ni-63	9.9×10^{-2}	—	—	9.9×10^{-2}	1.0×10^{-1}	—	—	1.0×10^{-1}
	Sr-90[d]	1.1	2.4×10^{-4}	2.3×10^{-5}	1.1	6.8×10^{-1}	1.5×10^{-4}	1.4×10^{-5}	6.8×10^{-1}
	Cs-137[d]	3.5×10^{-3}	—	1.7×10^{-2}	2.0×10^{-2}	2.4×10^{-3}	9.1×10^{-6}	1.2×10^{-2}	1.4×10^{-2}
	Pu-238	2.5×10^{-7}	3.7×10^{-5}	—	3.7×10^{-5}	2.5×10^{-7}	3.7×10^{-5}	1.0×10^{-9}	3.7×10^{-5}
	Pu-240	8.1×10^{-7}	1.2×10^{-4}	3.1×10^{-9}	1.2×10^{-4}	9.5×10^{-7}	1.4×10^{-4}	3.8×10^{-9}	1.4×10^{-4}
	Am-243	2.5×10^{-7}	1.1×10^{-5}	—	1.1×10^{-5}	3.1×10^{-7}	1.4×10^{-5}	—	1.4×10^{-5}
	Pu-239	8.2×10^{-7}	1.2×10^{-4}	3.3×10^{-9}	1.2×10^{-4}	1.0×10^{-6}	1.5×10^{-4}	4.3×10^{-9}	1.5×10^{-4}
	Am-241	7.1×10^{-6}	3.2×10^{-4}	3.6×10^{-6}	3.3×10^{-4}	8.2×10^{-6}	3.6×10^{-4}	4.3×10^{-6}	3.7×10^{-4}
	Totals	1.2	8.6×10^{-4}	1.7×10^{-2}	1.2	7.9×10^{-1}	8.7×10^{-4}	1.2×10^{-2}	8.1×10^{-1}
Bone (29/26)	Ni-63	3.0	—	—	3.0	3.1	—	—	3.1
	Sr-90[d]	4.5	9.8×10^{-4}	2.3×10^{-5}	4.5	2.7	5.9×10^{-4}	1.5×10^{-5}	2.7
	Cs-137[d]	4.0×10^{-3}	2.6×10^{-5}	1.7×10^{-2}	2.1×10^{-2}	2.8×10^{-3}	1.9×10^{-5}	1.2×10^{-2}	1.5×10^{-2}
	Pu-238	5.2×10^{-6}	7.7×10^{-4}	—	7.7×10^{-4}	5.0×10^{-6}	7.2×10^{-4}	1.0×10^{-9}	7.2×10^{-4}
	Pu-240	1.7×10^{-5}	2.5×10^{-3}	3.1×10^{-9}	2.5×10^{-3}	1.9×10^{-5}	2.7×10^{-3}	3.8×10^{-9}	2.7×10^{-3}
	Am-243	5.9×10^{-6}	2.6×10^{-4}	—	2.7×10^{-4}	6.9×10^{-6}	3.0×10^{-4}	—	3.1×10^{-4}
	Pu-239	1.7×10^{-5}	2.5×10^{-3}	3.3×10^{-9}	2.5×10^{-3}	2.1×10^{-5}	3.0×10^{-3}	4.3×10^{-9}	3.0×10^{-3}
	Am-241	1.6×10^{-4}	7.2×10^{-3}	3.6×10^{-6}	7.4×10^{-3}	1.8×10^{-4}	7.7×10^{-3}	4.4×10^{-6}	7.9×10^{-3}
	Totals	7.5	1.4×10^{-2}	1.7×10^{-2}	7.5	5.8	1.5×10^{-2}	1.2×10^{-2}	5.8
Lungs (6/7)	Tc-99	2.1×10^{-4}	—	—	2.1×10^{-4}	2.7×10^{-4}	—	—	2.7×10^{-4}
	Cs-137[d]	1.1×10^{-3}	1.0×10^{-5}	3.0×10^{-2}	3.1×10^{-2}	6.9×10^{-4}	6.5×10^{-6}	1.9×10^{-2}	1.9×10^{-2}
	U-235[d]	—	1.4×10^{-3}	—	1.4×10^{-3}	—	4.5×10^{-3}	—	4.5×10^{-3}
	Pu-238	3.6×10^{-7}	1.3×10^{-3}	1.2×10^{-9}	1.3×10^{-3}	3.7×10^{-7}	1.3×10^{-3}	1.2×10^{-9}	1.3×10^{-3}
	Pu-240	9.6×10^{-7}	3.4×10^{-3}	3.1×10^{-9}	3.4×10^{-3}	1.2×10^{-6}	4.2×10^{-3}	3.8×10^{-9}	4.2×10^{-3}
	Am-243	—	3.6×10^{-4}	—	3.6×10^{-4}	—	4.7×10^{-4}	—	4.7×10^{-4}
	Pu-239	9.7×10^{-7}	3.4×10^{-3}	3.3×10^{-9}	3.4×10^{-3}	1.3×10^{-6}	4.6×10^{-3}	4.3×10^{-9}	4.6×10^{-3}
	Am-241	3.0×10^{-6}	1.0×10^{-2}	3.8×10^{-6}	1.0×10^{-2}	3.5×10^{-6}	1.3×10^{-2}	4.5×10^{-6}	1.3×10^{-2}
	Totals	1.3×10^{-3}	2.0×10^{-2}	3.0×10^{-2}	5.1×10^{-2}	9.7×10^{-4}	2.8×10^{-2}	1.9×10^{-2}	4.8×10^{-2}
Thyroid (4/4)	I-129	1.8	1.7×10^{-3}	1.8×10^{-5}	1.8	2.3	2.1×10^{-3}	2.2×10^{-5}	2.3
	Cs-137[d]	—	—	3.1×10^{-2}	3.1×10^{-2}	—	—	2.1×10^{-2}	2.1×10^{-2}
	Totals	1.8	1.7×10^{-3}	3.1×10^{-2}	1.9	2.3	2.1×10^{-3}	2.1×10^{-2}	2.3
GI-LLI (1/1)	Sr-90[d]	—	2.9×10^{-6}	4.6×10^{-5}	4.9×10^{-5}	—	1.7×10^{-6}	2.8×10^{-5}	3.0×10^{-5}
	Cs-137[d]	—	3.6×10^{-7}	3.5×10^{-2}	3.5×10^{-2}	—	2.4×10^{-7}	2.2×10^{-2}	2.2×10^{-2}
	U-235[d]	2.9×10^{-5}	1.3×10^{-7}	—	2.9×10^{-5}	8.9×10^{-5}	4.2×10^{-7}	—	8.9×10^{-5}
	Th-234	—	1.2×10^{-6}	—	1.2×10^{-6}	—	3.8×10^{-6}	—	3.8×10^{-6}
	Pu-238	2.0×10^{-6}	1.0×10^{-7}	1.2×10^{-9}	2.1×10^{-6}	2.1×10^{-6}	1.1×10^{-7}	1.3×10^{-9}	2.2×10^{-6}
	Pu-240	5.2×10^{-6}	2.6×10^{-7}	3.1×10^{-9}	5.5×10^{-6}	6.3×10^{-6}	3.2×10^{-7}	3.8×10^{-9}	6.3×10^{-6}
	Pu-239	5.1×10^{-6}	2.7×10^{-7}	3.3×10^{-9}	5.4×10^{-6}	6.7×10^{-6}	3.5×10^{-7}	4.3×10^{-9}	7.0×10^{-6}
	Am-241	1.6×10^{-5}	8.2×10^{-7}	3.8×10^{-6}	2.0×10^{-5}	1.9×10^{-5}	9.8×10^{-7}	4.5×10^{-6}	2.3×10^{-4}
	Totals	5.8×10^{-5}	6.1×10^{-6}	3.5×10^{-2}	3.5×10^{-2}	1.2×10^{-4}	8.0×10^{-6}	2.3×10^{-2}	2.3×10^{-2}

(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

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16 ABSTRACT *(200 words or less)*

The purpose of the work reported here was to estimate the potential dose to man resulting from biotic transport mechanisms at a reference humid 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 during 500 years following site closure. Five-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-agricultrual 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 assessments 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.

17 KEY WORDS AND DOCUMENT ANALYSIS

17a DESCRIPTORS

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17b IDENTIFIERS/OPEN ENDED TERMS

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