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

Phase I - Final Report

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Pacific Northwest Laboratory
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ABSTRACT

Licensing and regulation of commercial low-level waste (CLLW) burial facilities require that anticipated risks associated with burial sites be evaluated for the life of the facility. This work reviewed the existing capability to evaluate dose to man resulting from the potential redistribution of buried radionuclides by plants and animals that we have termed biotic transport. Through biotic transport, radionuclides can be moved to locations where they can enter exposure pathways to man. We found that predictive models currently in use did not address the long-term risks resulting from the cumulative transport of radionuclides. Although reports in the literature confirm that biotic transport phenomena are common, assessments routinely ignore the associated risks or dismiss them as insignificant without quantitative evaluation. To determine the potential impacts of biotic transport, we made order-of-magnitude estimates of the dose to man for biotic transport processes at reference arid and humid CLLW disposal sites. Estimated doses to site residents after assumed loss of institutional control were comparable to dose estimates for the intruder-agricultural scenario defined in the DEIS for 10 CFR 61 (NRC). The reported lack of potential importance of biotic transport at low-level waste sites in earlier assessment studies is not confirmed by order of magnitude estimates presented in this study.

EXECUTIVE SUMMARY

This report summarizes the results of Phase I of our efforts to evaluate the relevance of biotic transport to the assessment of impacts used in licensing and regulation of commercial low-level waste disposal sites. Numerous examples from the literature indicate that plants and animals in the vicinity of waste sites do become contaminated as a result of contact with radioactive materials. However, we could find no reports of detailed studies conducted to evaluate the rates of radionuclide movement at commercial low-level waste (CLLW) by biotic processes. A review of the existing dose assessment models showed a lack of predictive risk capabilities associated with long-term radionuclide mobilization by the biota. Commonly, impact assessments treated biotic transport by ignoring it or by stating that the risks were assumed to be negligible.

Once having established that the methodology for risk assessment was lacking, we set about to develop order-of-magnitude estimates for the potential dose to man resulting from biotic transport at representative arid and humid sites. Reference site descriptions were established which considered waste inventories, site characteristics and biological communities. A biotic transport model was established for plant and animal intrusion into buried wastes. Parameter values were obtained from the literature. We then coupled the biotic transport model to an existing computer code and calculated dose to individuals inhabiting the waste site after loss of institutional control. We compared the estimated dose to humans from biotic transport mechanisms with doses to humans estimated for the intruder-agricultural scenario reported in the DEIS for 10 CFR 61 (NRC). The dose to man as a result of cumulative biotic transport processes was calculated to be the same order of magnitude as the dose resulting from the more commonly evaluated human intruder scenario.

The previously reported lack of potential importance of biotic transport at CLLW sites is not confirmed by our findings. The accumulated activities of generations of plants and animals at both arid and humid sites appear to be capable of moving radionuclides to locations where they can cause exposure to man.

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1.0 INTRODUCTION

Commercial low-level waste disposal facilities may be envisioned to proceed through several stages of development during their "lifetimes." An initial period of active disposal may be followed by a period of years during which site monitoring and/or maintenance are the only activities. Ultimately, institutional controls will be lost and site management practices abandoned. Throughout these successive phases, which may encompass several hundred years, plant and animal communities will occupy the site.

The role of plants and animals in transporting wastes from burial sites to locations where they might cause human exposure can potentially be an important consideration in regulatory and licensing decisions. Literature reports give examples of plant and animal entry into buried wastes, while assessment studies report that the roles of plants and animals are insignificant. Recent technological development work includes testing the effectiveness of intrusion barriers to plants and animals over simulated wastes. The uncertainties about the relevance of biotic pathways to the long-term regulation of nuclear waste disposal have led to this evaluation.

The general approach used in phase I includes an examination of the literature on plant and animal intrusion into buried wastes, a review of commonly used dose assessment models to identify nonagricultural biotic pathway components, and exposure scenario development followed by order-of-magnitude dose assessments for biotic pathways at reference arid western and humid eastern sites.

2.0 PHASE I, TASKS 1 AND 2: EVALUATION OF EXISTING MODELS AND THE POTENTIAL ROLE OF BIOTIC TRANSPORT MODELS

Two potentially conflicting statements or concerns exist in the literature concerning radiation exposure pathways. One position is typified by Clarke and Webb (1979) who advocate a model evaluation of all isotopes via all pathways. The second position, exemplified by Adam and Rogers (1978), and typically the current application practice, is to assume that biotic pathways need not be evaluated by rigorous techniques, i.e. modeling.

As a result of the Tasks 1 and 2 of this project, we conclude that in-depth studies of radionuclide movement through the biota associated with commercial low-level waste (CLLW) burial sites have not been conducted, though a number of specific examples of biotic transport have been observed. In addition, laboratory experiments and field observations have demonstrated biotic mechanisms and processes through which radionuclides are transported. The inferences for biotic transport potential are relatively clear. What is not known, and has not been assessed, is the magnitude and potential consequences of transport over times up to 500 years (McKenzie et al. 1982).

This chapter contains a summary of our findings from Tasks 1 and 2 of Phase I of this project: the evaluation of existing models and a definition of the potential role of future biotic transport models. After establishing definitions, we summarize our review of existing radiation dose pathway models, commercial low-level waste management literature, and biotic transport evidence from recent scientific literature. Finally, we present our recommendations for establishing the potential magnitude of biotic transport and for assessing the role of biotic transport in commercial low-level waste management decisions.

2.1 DEFINITIONS

Fundamental definitions for some of the terms used in this report are given below. These definitions are intended to apply specifically to commercial low-level waste management and biotic transport.

Transport Mechanism. The means or process by which radioactive material is moved from one place to another. The mechanisms of particular concern in this study are those that move radioactive materials from waste containers, burial trenches, or disposal sites. Three basic transport mechanisms may be important: atmospheric transport, ground-water transport, and biotic transport.

Biotic Transport. Actions of plants or animals that transport or cause transport of radioactive materials from a CLLW burial ground to a location where these materials can enter into human exposure pathways such as food chains.

Radiation Exposure Pathways. Routes by which radionuclides or radiation may reach people. Examples of radiation exposure pathways resulting from the action of transport mechanisms at CLLW burial grounds include:

- ingestion of well water from the saturated zone during ground-water transport of radioactive materials
- ingestion of aquatic foods taken from a nearby river, which has been contaminated by overland flow or transport through the saturated zone
- ingestion of food crops irrigated with contaminated water or grown in contaminated soil
- direct irradiation from contaminated soil and
- inhalation of radionuclides resuspended with contaminated soil.

Human Food Chain Components. Plant or animal materials that are typically eaten by man. These include above- and belowground vegetable crops, fruits, berries, grains, eggs, milk, beef, pork, poultry, fish, crustacea, molluscs, and water plants.

2.2 REVIEW AND COMPARISON OF RADIONUCLIDE TRANSPORT MODELS, RADIATION EXPOSURE PATHWAY MODELS, AND RECENT COMMERCIAL LOW-LEVEL WASTE MANAGEMENT STUDIES

Existing radionuclide transport and radiation exposure pathway models were reviewed to determine the current status of biotic transport modeling. Models chosen for review were identified through discussions with personnel at the Pacific Northwest Laboratory who had participated in model development efforts, and through model compilation studies (Mosier et al. 1980; Owen et al. 1979; Strenge et al. 1976; Hoffman et al. 1977; Miller 1978; Science Applications, Inc. 1979). The review resulted in a list of 23 computer programs for further evaluation (Table 2.2-1). After the computer programs were identified, they were classified and compared.

The computer programs identified for review (Table 2.2-1) use essentially the same methods and equations. Most are actually modifications of previously written programs. The computer program PABLM (Napier et al. 1980a), for example, which calculates an accumulated dose, is similar to the computer programs FOOD and ARRRG (Napier et al. 1980b), which calculate a one-year dose and a 50-year dose commitment. FOOD and ARRRG are simplifications of the computer program HERMES (Fletcher and Dotson 1971). Other variations of FOOD include GAUCHE (Mosier et al. 1980) and VITTLS (Brenchley et al. 1977), while CARDOCC (Watts 1976) is a modification of ARRRG. Of these eight programs, the three selected for further examination in this study include only FOOD, ARRRG and CRITR. RAGTIME (Pleasant et al. 1980), developed to account both for seasonality of agricultural processes and the generation of radioactive daughters through decay during food chain transport, is basically a modification of the previously developed computer program TERMOD (Booth and

TABLE 2.2-1. Computer Programs Reviewed

Computer Program	Authors
AIRDOS II (1)	Moore 1977
*AIRDOS-EPA	Moore et al. 1979
AIRWAY (3)	Rider 1979
*AQUAMAN	Shaeffer and Etnier 1979
*ARRRG	Napier et al. 1980b
BELCH (2)	Mosier et al. 1980
*BIODOSE	Duffy and Bogar 1980
BIOTRAN (3)	Gallegos et al. 1980
CARDOCC (1)	Watts 1976
*CRITR	Soldat et al. 1974
*FOOD	Napier et al. 1980b
GAUCHE (1)	Mosier et al. 1980
HERMES (1)	Fletcher and Dotson 1971
INGDOS (1)	Pleasant 1979
LADTAP (2)	Mosier et al. 1980
*MILDOS	Strenge and Bander 1981
PABLM (2)	Napier et al. 1980a
RAGTIME (1,2)	Pleasant et al. 1980
*RVRDOS	Martin et al. 1976
*TERMOD	Booth and Kaye 1971
UDAD (1)	Momeni et al. 1979
VADOSCA (2)	Miller 1978
VITTLS (1)	Brenchley et al. 1977
2BPUFF (1)	Crawford 1966

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*Designates a model chosen for extensive review.

Reasons for Removal from Further Consideration

1. Redundant; capabilities available in other programs or precursor or descendant of program reviewed.
2. Incomplete documentation.
3. Overly detailed in analysis or parameters not all available.

Kaye 1971). Because the development of RAGTIME was still in progress, only the program TERMOD was reviewed. The transport mechanism and radiation exposure pathway equations found in AIRDOS-EPA (Moore et al. 1979), which is a modified version of AIRDOS-II (Moore 1977), and the equations in INGDOS (Pleasant 1979) are exactly the same. Thus, the AIRDOS-EPA computer program was chosen for review in this study. MILDOS (Strenge and Bander 1981) is an NRC version of the UDAD computer program (Momeni et al. 1979).

Some computer programs weren't considered because they were redundant. This category included computer programs such as 2BPUFF (Crawford 1966), where information is contained in other computer programs. Computer programs were also not included if sufficient code documentation did not exist or if they were not easily obtainable. These included: LADTAP (Mosier et al. 1980), BELCH (Mosier et al. 1980), and VADOSCA (Miller 1978). Other computer programs were eliminated if they were overly detailed in their analysis of a specific process; that is, if it would be impossible to obtain proper parameter values to simulate other transport mechanisms, or if equations could not easily be changed to calculate concentration as opposed to dose. These included AIRWAY (Rider 1979) and BIOTRAN (Gallegos et al. 1980).

The radionuclide transport and radiation exposure pathway computer programs listed in Table 2.2-1 consider only atmospheric and surface water transport mechanisms. None of the programs directly considers biotic transport mechanisms. The exposure pathway models calculate concentrations in human food stuffs, with no attempts to model radionuclide transport by non-food chain biota. All of the computer programs were developed to conduct radiation dose analyses following radionuclide releases from operating nuclear facilities or fallout. These programs do not consider potential long-term impacts on the integrity of buried waste containers in CLLW trenches or the increase in accessibility of the buried wastes resulting from biotic mechanisms. A more detailed discussion of our review of existing models can be found in McKenzie et al. (1982).

Recent studies on CLLW disposal were reviewed, and they includ[illegible]ussions of impact analysis, waste classification, environmental ass[illegible]and decommissioning. No studies were found, however, that spec[illegible]ess biotic transport mechanisms. The studies reviewed utilize[illegible]l models designed to evaluate transport by biota not directly [illegible]e human food chain.

Typical statements concerning biotic transport in recent comm[illegible]w-level waste management studies include:

- "During the conduct of the study, numerous pathways have been and will continue to be considered. However, many of these pathways are either not restricting or are highly improbable. Only those reasonable pathways which are restricting are considered in detail." (Adam and Rogers 1978, p. 17)
- "NRC staff believes, however, that the most significant pathway is ground-water migration. ... Impacts from plant and animal intrusion are site-specific and can be reduced through engineering designs applied to reduce ground-water migration and potential intruder exposures" (U.S. NRC 1981)
- "ecological pathways involving the movement of waste material by waterfowl, burrowing animals, blowing weeds, etc., are not considered in this study" (Murphy and Holter 1980, p. 8-12)

A further review of recent low-level waste management literature and the potential implications on biotic transport modeling can be found in McKenzie et al. (1982).

2.3 BIOTIC TRANSPORT IN TERRESTRIAL AND AQUATIC SYSTEMS

Terrestrial biota may be involved in the transport of radionuclides from a commercial low-level waste burial ground by transport enhancement, intrusion/active transport, or by secondary transport.

In transport enhancement, biota can enhance radionuclide transport by altering the waste environment or the waste form itself. Potentially toxic waste products become more mobile as a result, usually through some means (often physical or biochemical) other than movement by the organisms initially involved.

Intrusion/active transport is the process most commonly considered for biotic transport of radionuclides from buried waste. Plant roots or burrowing animals may penetrate the waste zone. Plant roots translocate radioactive material through stems to the aboveground portion of the plants (Rickard and Klepper, 1976). Burrowing mammals and invertebrates can penetrate the earthen covers over shallow burried wastes and move contaminants to the soil surface (Paine et al. 1979).

Biota may mobilize radionuclides from low-level waste burial sites through secondary transport. In these secondary transport processes radionuclides are available to the biota for horizontal displacement only after they have been initially mobilized by some other means. Webster (1979) reports that radionuclides leached from buried waste at Oak Ridge National Laboratory return to the surface environment by "seeps" or overflow from water that accumulates in burial trenches. Once at the surface, any number of transport pathways could develop from animals using the water. Hakonson and Bostick (1976), for example, point to use of contaminated surface water by bees as a means for contamination of the bees and their honey. More complete descriptions of biotic transport in terrestrial systems and general observations from the field are given in McKenzie et al. (1982).

Radionuclides from commercial low-level waste (CLLW) burial grounds can directly reach surface water bodies via two routes: (1) overland water flow, which erodes overburden and subsequently flows through the wastes, transporting radionuclides to lakes and streams, or (2) leaching of buried wastes by ground water and subsequent movement of the contaminated water to the water table and eventually to surface waters. The former case is most likely following the loss of institutional controls. Once the site is breached, transport to aquatic sites may be rapid. Movement to surface waters via ground water would be relatively slow; concentrations would likely be low because of radioactive decay, filtration and selective adsorption to soil particles. Although considerable information is available concerning cycling of radionuclides in aquatic food webs, essentially no data are available documenting biotic transport via aquatic organisms from CLLW burial sites.

We believe that radionuclide transport of CLLW contaminants by aquatic organisms could involve only secondary transport processes of such small relative magnitude, when compared to terrestrial systems, that we dismiss them from further consideration.

2.4 RECOMMENDATIONS FROM PHASE I, TASKS 1 AND 2

Licensing decisions regarding commercial low-level waste (CLLW) management are, of necessity, influenced by the results of predictive modeling. Our review of recent literature on low-level waste indicates that a long-term scenario analysis approach is typically used in predictive modeling exercises. In such an approach, radionuclide transport models are coupled with radiation dose evaluation models through the use of long-term human exposure scenarios. The resulting doses or estimates of impact on human health are then used as input to decisions about siting, trench design, burial ground operation, waste packaging, waste form, and ultimately, decommissioning.

All of the modeling exercises reviewed here are based on the assumption that burial ground performance is most strongly affected by the long-term actions of air and water. None of the models considers biotic mechanisms and processes other than those that are directly linked to man through the human food chain. Biotic transport has not been evaluated beyond the qualitative level in current radioactive waste disposal impact assessments. However, statements about the lack of concern for significant effects from biotic transport are not supported by operational experience or by an evaluation of biotic transport mechanisms and processes. Based on this review, an evaluation of the potential magnitude of biotic transport and its impact is needed to assess the adequacy and reliability of the current licensing and regulatory processes for CLLW disposal sites.

We find that all current dose pathway models are essentially the same and deficient in that they do not include biotic transport. We conclude that the results of radiological impact assessments are highly dependent on the scenario examined. Additionally, current assessment procedures may not be ideally suited for use with the long-term scenarios of concern.

As a result of our efforts in the first two tasks of Phase I of this project, we recommended that a defensible, reproducible method be developed to quantify the long-term impacts of biotic transport mechanisms.

As a first step of Task 3 of Phase I, we recommended that order of magnitude relationships be developed and applied to a specific scenario (such as the crop root penetration scenario). This step will begin by extending the current scenario to include the full range of plant and animal species occurring on or near the waste site. The calculated results of the scenario with and without biotic transport will be compared.

The second step of Task 3 was recommended to determine the elapsed time required for biotic mechanisms and processes to become part of a plausible pathway for human exposure. Knowledge of this would permit the development of biotic transport scenarios that specifically address the times of critical importance.

The third step of Task 3 was recommended to develop first order approximations for the rates or magnitudes of materials transported by each biotic mechanism. Existing field data should be used wherever possible to quantify these transport mechanisms. Much of this effort must rely on incomplete or inferential data and limited ecological understanding. However, the information obtained in this task should be a valuable tool for determining the CLLW disposal licensing implications of biotic transport processes.

A summary of the results of Task 3 of Phase I of this project, the development and results of an order-of-magnitude estimate of the impacts of biotic transport are given in Section 3.0.

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3.0 PHASE I, TASK 3: ORDER-OF-MAGNITUDE ESTIMATES FOR ARID AND HUMID COMMERCIAL LOW-LEVEL WASTE DISPOSAL SITES

Three biotic transport mechanisms are possible at a waste disposal site: 1) transport enhancement, 2) intrusion and active transport, and 3) secondary transport (McKenzie et al. 1982a). In transport enhancement, plants and animals modify the waste containers or trench covers so that the potential for radionuclide transport by abiotic pathways is increased. 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 transported by the biota after they have escaped burial site containment.

In Task 3 of Phase I of this project, only intrusion and active transport by biota were considered. An initial qualitative assessment indicated that intrusion and 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.

In this report, two processes are considered within intrusion and active transport. They are 1) direct intrusion into buried waste by burrowing mammals and invertebrates and 2) penetration by plant roots, followed by movement of radionuclides by the biota. These two processes can result in transport and redistribution of radionuclides within the low-level waste trench cover and to 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 Task, we considered 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. Thus, we developed order-of-magnitude estimates for the biotic communities corresponding to reference western arid and eastern humid commercial low-level waste disposal sites. The assessment includes consideration of long-term events such as community succession. Waste inventories and disposal scenarios are examined for both current and anticipated waste treatment practices, as these will also influence the magnitude of biotic transport.

This section contains a summary of our findings from Task 3 of Phase I of this project: the development of an order-of-magnitude estimate of the potential impacts of biotic transport for arid and humid low-level waste disposal sites. After developing reference arid and humid site descriptions, we describe the radiation exposure scenarios and the resulting source terms. Using these source terms, we describe the dose calculations and discuss the meaning of the results generated.

3.1 REFERENCE SITE DESCRIPTIONS

To assist in determining the importance of biotic transport at commercial low-level waste (CLLW) burial grounds, we have defined reference arid and humid sites and waste inventories. The site descriptions are constructed to represent conditions at sites currently operating in the United States, although not all of the features of the reference sites are exactly the same as those encountered at 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 CLLW burial grounds and establish the representative parameters that we used in the analysis. We also briefly describe the arid and humid site environments. Finally, we develop the waste spectra for both current and future waste forms.

3.1.1 Reference Commercial Low-Level Waste Burial Grounds

Two commercial low-level waste (CLLW) burial grounds are located in the western United States and four commercial burial grounds either have operated or are operating in the eastern United States. The two western sites are located in Beatty, Nevada and Richland, Washington. The four eastern sites include Sheffield, Illinois; West Valley, New York; Morehead, Kentucky; and Barnwell, South Carolina. The Barnwell site is the only currently operating eastern site. A review of the site characteristics and operating practices can be found in Murphy and Holter (1980, Tables 3.1-2 and 3.1-3).

Radioactive waste disposal operations are generally similar to conventional sanitary landfill operations, with additional care taken in operations concerning the handling of radioactive materials. Waste containers are generally buried randomly as received. For the western sites, burial occurs in open, unlined trenches. For the eastern sites, the waste containers are protected from contact with rain water through daily application of earth backfill or through the use of temporary covers such as tarps. Each trench contains a mixture of radionuclides, waste forms, and types of containers. For the western sites, typically 1 to 2 m of mounded excavated earth fill is used as cover on the burial trenches. For the eastern sites, typically about 1 to 3 m of soil or clay is mounded over the top of each waste trench (Murphy and Holter 1980, Sec. 3.1.1).

Generic CLLW burial grounds were used in this project to provide a uniform basis for a comparative analysis. Such burial grounds have been defined in a conceptual decommissioning study by Murphy and Holter (1980, Section 7.0). Some of the features of the reference sites and facilities may not be exactly the same as those encountered at actual CLLW sites. However, the use of representative parameters will aid in estimating and comparing impacts from a biotic transport scenario with those from a human intrusion scenario. The following key assumptions are made for the reference shallow-land burial facilities:

- 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.

Both the western and eastern reference sites are assumed to be located on an upland area of generally flat terrain (Figure 3.1-1). Further information on the reference sites may be found in documents by McKenzie et al. (1982b; 1982a).

The plot plan for both the western and eastern reference commercial burial grounds is shown in Figure 3.1-2. Total site area is assumed to be about 70 ha. The sites are 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

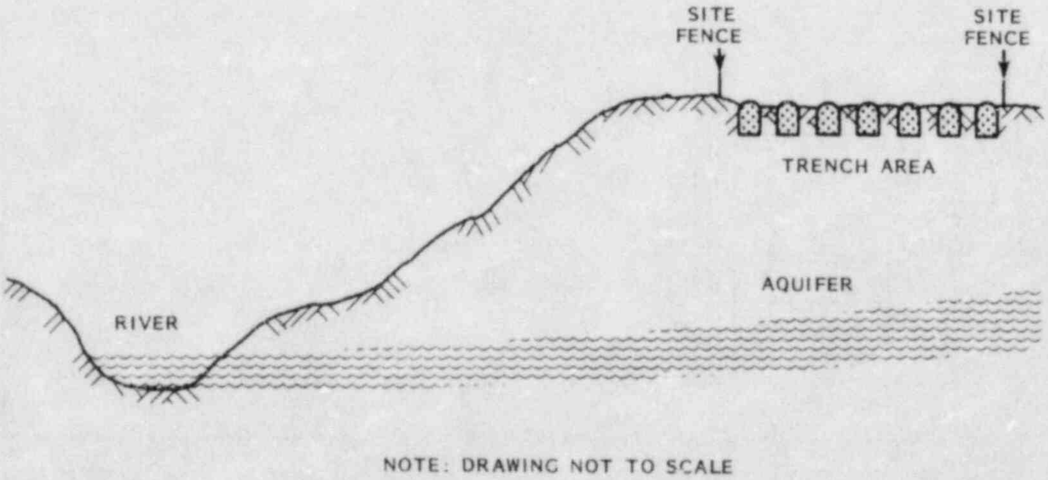

FIGURE 3.1-1. Schematic Cross Section of the Reference CLLW Burial Grounds

TABLE 3.1-1. Parameters for the Reference Western and Eastern CLLW Burial Grounds

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

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

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 3.1-1. For both the western and eastern sites, the total

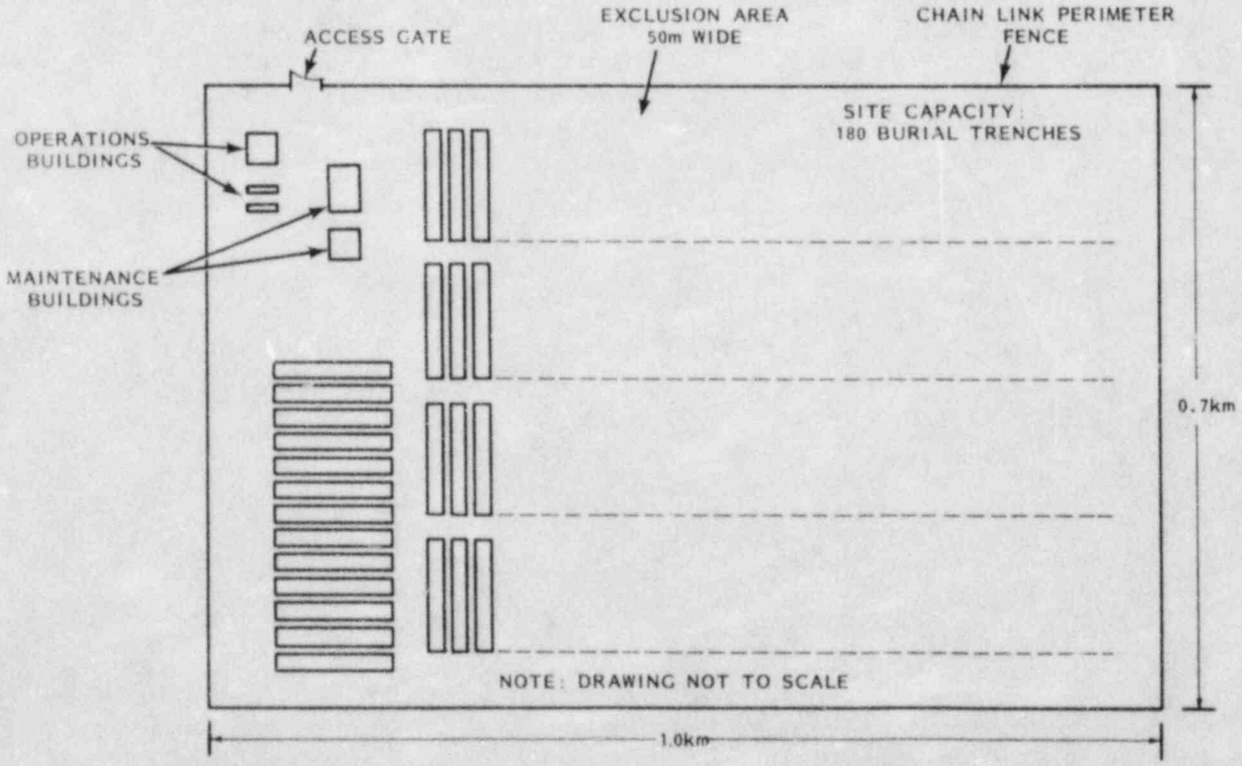

FIGURE 3.1-2. Plot Plan for the Reference Western and Eastern CLLW Burial Ground

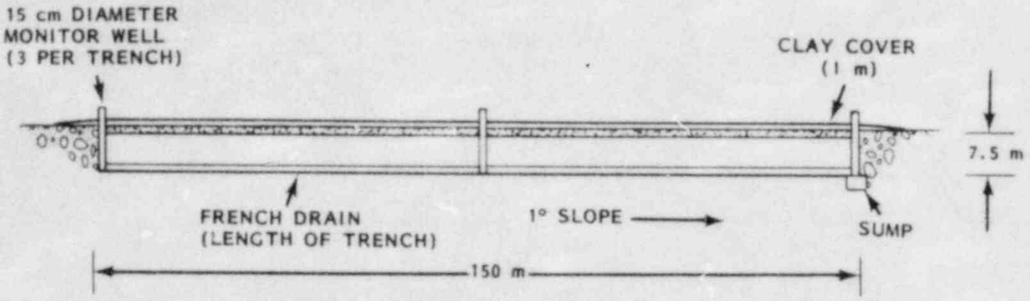

FIGURE 3.1-3. Reference Western Site CLLW Burial Trench

waste capacity is about 1.5 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 3.1-3 shows the dimensions and design of a reference western CLLW trench. Figure 3.1-4 shows the cross-section design of the reference eastern CLLW trench. A minimum space of 3 m is assumed between the top edges of adjacent trenches.

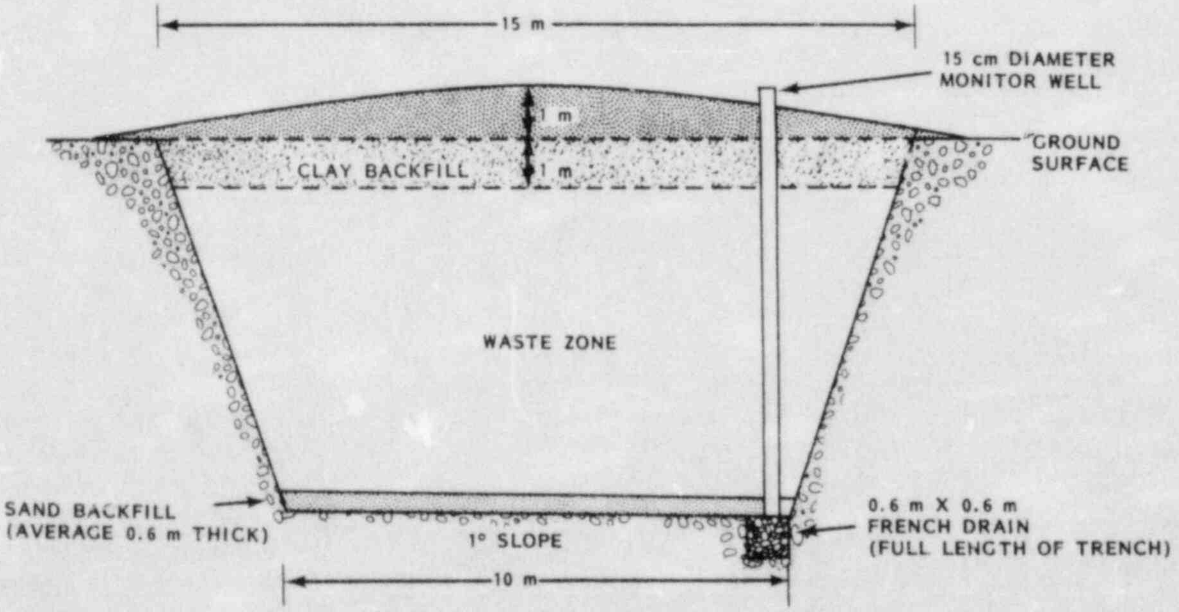

FIGURE 3.1-4. Cross Section View of the Reference Eastern CLLW Site Trench

3.1.2 Reference Radionuclide Inventories

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 CLLW 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 $6.5 \times 10^5 m^3$ of CLLW will be generated in the western United States, and about $9.7 \times 10^5 m^3$ of CLLW will be generated in the eastern United States.

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 analysis, we used the decayed isotopic concentrations for the western and eastern 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 CLLW waste streams are solidified. No volume reduction processes are assumed, and with no reduction in volume, void spaces increase the instability of the container. 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.

The six decayed composite waste streams considered in this task were:

- solid reactor wastes
- solidified liquid reactor wastes
- uranium conversion and fuel fabrication waste

TABLE 3.1-2. Decayed Radionuclide Concentrations for Reference Western and Eastern Waste Spectra[a]

	Reference Western Site		Reference Eastern Site	
Radionuclide	Total for Waste Spectrum 1 (Ci/m^3)	Total for Waste Spectrum 2 (Ci/m^3)	Total for Waste Spectrum 1 (Ci/m^3)	Total for Waste Spectrum 2 (Ci/m^3)
H-3	4.0E-02[b]	6.2E-02	2.8E-02	3.6E-02
C-14	4.0E-03	5.3E-03	2.2E-03	3.0E-03
Fe-55	5.0E-01	6.2E-01	6.3E-01	7.8E-01
Ni-59	1.7E-03	2.1E-03	2.2E-03	2.6E-03
Co-60	1.4E+00	1.7E+00	1.7E+00	2.1E+00
Ni-63	1.4E-01	1.7E-01	1.8E-01	2.1E-01
Nb-94	5.4E-05	6.7E-05	6.8E-05	8.4E-05
Sr-90	4.1E-03	5.2E-03	4.1E-03	4.7E-03
Tc-99	6.4E-05	7.8E-05	7.8E-05	9.8E-05
I-129	1.7E-04	2.1E-04	2.2E-04	4.2E-06
Cs-135	6.4E-05	7.8E-05	8.0E-05	9.8E-05
Cs-137	1.4E+00	1.8E+00	1.8E+00	2.2E+00
U-235	2.9E-05	8.7E-05	2.2E-05	6.3E-05
U-238	2.9E-05	5.4E-04	1.3E-04	3.9E-04
Np-237	9.6E-11	1.2E-10	1.2E-10	1.4E-10
Pu-238	5.2E-04	5.8E-04	6.3E-04	8.3E-04
Pu-239/240	4.4E-04	5.9E-04	5.5E-04	7.0E-04
Pu-241	1.4E-02	1.9E-02	1.8E-02	2.3E-02
Pu-242	9.7E-07	1.3E-06	1.2E-06	1.5E-06
Am-241	3.8E-04	5.3E-04	4.8E-04	6.1E-04
Am-243	2.3E-05	3.2E-05	2.8E-05	3.7E-05
Cm-243	4.2E-07	6.1E-07	5.1E-07	6.9E-07
Cm-244	2.7E-04	3.8E-04	3.2E-04	4.3E-04
Totals	3.5E+00	4.2E+00	4.5E+00	5.3E+00

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

(b) Where 4.0E-02 = 4.0×10^{-2}.

- industrial and institutional wastes
- liquid scintillations wastes
- biowastes.

A summary of the total waste spectra for the western and eastern sites reveals the average 20-year decayed waste concentrations (Table 3.1-2). 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.

3.1.3 Reference Environments

The reference arid site environment assumed 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.

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.

Among the animal communities at both sites, 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.

3.2 SCENARIO AND SOURCE TERM DEVELOPMENT

To permit a comparative evaluation of the long-term impacts of biotic transport processes at the reference western and eastern sites, 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 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.

3.2.1 Human Intrusion Scenarios from 10 CFR Part 61

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 task, we used 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 hold 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:

$$\lambda_A = \ln 2/t_{A_{1/2}} \quad (3.2)$$

where λ_A is defined for Equation 3.1 and where:

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

It is difficult to make an accurate statement about the durability of buried waste containers and the associated availability of wastes for biotic transport. Rough estimates of the durability of waste containers buried at arid western sites can be made by reviewing information from Card 1977 and McKinley and McKinney 1978. Waste materials and drums were exhumed approximately 15 years after burial. Based on the condition of those wastes and containers, we have inferred that approximately one-fourth of such wastes buried in similar trenches would be available for biotic transport.

Information on the durability of buried wastes containers for a humid eastern site is presented in Horton 1977. The wastes exhumed had been buried for approximately 15 years. Based on the condition of those wastes and containers, we inferred that approximately one-half of waste in a similar humid site would be available for biotic transport.

For this study, two container decomposition half-times are assumed for each reference site. Waste spectrum 1 is designed to represent current and past CLLW disposal conditions, with container decomposition time calculated from the inferred biotic availability of wastes exhumed at arid and humid sites. The containers and waste forms are assumed to decompose with a 35-year half-time for western sites, and a 15-year half-time for eastern sites. 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 for western wastes and a 50-year half-time for eastern wastes.

The surface soil concentrations developed for the intruder-agriculture scenario are shown in Table 3.2-1. Concentrations are also shown for waste spectra 1 and 2 after loss of institutional controls at the western and eastern sites, 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 either the western or eastern 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 is exposed for 2000 hours per year to penetrating radiation from the contaminated surface soil. These parameters and exposure conditions were used in radiation dose calculations, and the resulting doses were compared with doses resulting from biotic transport processes.

3.2.2 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), 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.

Plant Intrusion

Plants redistribute radionuclides from the buried wastes by uptake through the root system and assumed subsequent uniform distribution of contaminants throughout the plant. It was 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 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

TABLE 3.2-1. Summary of the Surface Soil Radionuclide Concentrations Resulting from the Intruder-Agriculture Scenario at the Reference Western and Eastern Sites(a)

Radionuclide	Reference Western Site		Reference Eastern Site	
	Total for Waste Spectrum 1(b) (pCi/m^2)	Total for Waste Spectrum 2(b) (pCi/m^2)	Total for Waste Spectrum 1(b) (pCi/m^2)	Total for Waste Spectrum 2(b) (pCi/m^2)
H-3	1.1E+07(c)	8.4E+06	8.5E+06	8.9E+06
C-14	2.8E+08	2.0E+08	1.8E+08	1.8E+08
Fe-55	2.6E-01	1.9E-01	3.7E-01	3.5E-01
Co-60	1.9E+05	1.4E+05	1.8E+08	1.6E+08
Ni-59	1.2E+08	8.8E+07	2.7E+05	2.4E+05
Ni-63	4.9E+09	3.6E+09	7.2E+09	6.4E+09
Sr-90	2.6E+07	1.9E+07	2.9E+07	2.6E+07
Y-90	2.6E+07	1.9E+07	2.9E+07	2.6E+07
Tc-99	4.6E+06	3.3E+06	6.4E+06	6.1E+06
I-129	1.2E+07	8.8E+06	1.8E+07	1.6E+07
Cs-135	4.6E+06	3.3E+06	6.6E+06	6.1E+06
Cs-137	1.0E+10	7.3E+09	1.5E+10	1.4E+10
Ba-137m	9.5E+09	6.9E+09	1.4E+10	1.3E+10
U-235	2.0E+06	1.5E+06	1.8E+06	3.9E+06
Th-231	2.0E+06	1.5E+06	1.8E+06	3.9E+06
Np-237	6.9E+00	5.0E+00	9.9E+00	8.7E+00
U-238	2.0E+06	1.5E+06	1.1E+07	2.4E+07
Th-234	2.0E+06	1.5E+06	1.1E+07	2.4E+07
Pu-238	1.7E+07	1.2E+07	2.4E+07	2.4E+07
Cm-244	4.2E+05	3.1E+05	5.7E+05	5.8E+05
Pu-240	1.5E+07	1.1E+07	4.4E+07	4.4E+07
Cm-243	2.7E+03	1.9E+03	3.7E+03	3.8E+03
Am-243	1.7E+06	1.2E+06	2.3E+06	2.3E+06
Np-239	1.7E+06	1.2E+06	2.3E+06	2.3E+06
Pu-239	1.5E+07	1.1E+07	4.4E+07	4.4E+07
Pu-241	8.2E+06	6.0E+06	1.2E+07	1.2E+07
Am-241	5.3E+07	3.8E+07	7.7E+07	7.4E+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 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.

(c) Where 1.1E+07 = 1.1×10^{7}.

(b) Where 4.0E-02 = 4.0×10^{-2}.

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.

Vegetative cover for the western 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 McKenzie et al. (1982b). 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.

Vegetative cover on the eastern commercial 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). Further details about the plant community for the eastern site are given in McKenzie et al. (1982c).

Animal Intrusion

Potential animal intruders for the western site include a number of burrowing species. These animals were classified into six groups of animals 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 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 commercial low-level waste burial site.

Potential animal burrowers at the eastern site include the eastern chipmunk (Tamias striatus), woodchuck (Marmota monax), moles (Parascalops breweri, Scalopus aquaticus, Condylura cristata), ants, and earthworms. 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 commercial low-level waste burial site.

Further details on the animal population densities, burrow volumes, depth distribution of burrow systems, and the estimated volumes of soil brought to the surface are given in reports by McKenzie et al. (1982b; 1982c).

3.2.3 Calculations of Biotic Transport

The BIOPORT computer program calculates BIOlogical transPORT of radionuclides from a commercial 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. (1982b). 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 each soil 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 above ground plant parts.

3.2.4 Source Terms

A summary of the source terms resulting from intrusion and active biotic transport processes for waste spectra 1 and 2 at the western and eastern sites are shown in Table 3.2-2. 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 periods until the peak surface radionuclide concentrations are reached. For the western site, the quantities of radionuclides that accumulate in the soil layers above the

TABLE 3.2-2. Summary of the Surface Soil Concentrations Resulting from Intrusion and Active Biotic Transport Processes at the Reference Western and Eastern Sites(a)

Radionuclide	Reference Western Site		Reference Eastern Site			
	Waste Spectrum 1(b) at 100 Years (pCi/m^2)	Waste Spectrum 2(b) at 100 Years (pCi/m^2)	Waste Spectrum 1(b) 100 Years (pCi/m^2)	Waste Spectrum 1(b) 237 Years (pCi/m^2)	Waste Spectrum 2(b) 100 Years (pCi/m^2)	Waste Spectrum 2(b) 266 Years (pCi/m^2)
H-3	7.0E+04(c)	7.3E+04	7.1E+03	8.1E+00	5.9E+03	1.9E+00
C-14	1.4E+06	1.2E+06	1.3E+05	3.5E+05	1.0E+05	4.3E+05
Fe-55	1.4E-03	1.1E-03	4.9E-04	--(d)	3.6E+04	--(d)
Co-60	2.9E+03	2.3E+03	5.9E+06	3.0E+07	4.2E+06	3.7E+07
Ni-59	3.1E+06	2.6E+06	4.4E+03	3.2E-04	3.1E+03	--(d)
Ni-63	1.3E+08	9.9E+07	2.3E+08	4.5E+08	1.7E+08	4.5E+08
Sr-90	5.7E+06	4.8E+06	9.9E+06	1.8E+06	6.9E+06	1.1E+06
Y-90	5.7E+06	4.8E+06	9.9E+06	1.8E+06	6.9E+06	1.1E+06
Tc-99	1.3E+06	1.0E+06	2.7E+06	1.4E+07	2.1E+06	1.8E+07
I-129	3.2E+05	2.6E+05	6.2E+05	3.2E+06	4.5E+05	4.0E+06
Cs-135	3.3E+04	2.6E+04	2.7E+04	1.3E+05	2.0E+04	1.6E+05
Cs-137	7.3E+07	6.1E+07	6.0E+07	1.2E+07	4.5E+07	8.0E+06
Ba-137m	7.0E+07	5.8E+07	6.0E+07	1.2E+07	4.5E+07	8.0E+06
U-235	1.7E+04	3.1E+04	8.9E+03	4.3E+04	1.5E+04	1.3E+05
Th-231	1.7E+04	3.1E+04	8.9E+03	4.3E+04	1.5E+04	1.3E+05
Np-237	5.3E-02	4.4E-02	4.8E-02	2.3E-01	3.4E-02	2.8E-01
U-238	1.7E+04	2.0E+05	5.3E+04	2.5E+05	9.6E+04	7.9E+05
Th-234	1.7E+04	2.0E+05	5.3E+04	2.5E+05	9.6E+04	7.9E+05
Pu-238	9.0E+04	6.5E+04	2.7E+04	3.3E+04	2.1E+04	3.4E+04
Cm-244	2.1E+01	3.1E+03	2.8E+03	7.2E+01	2.3E+03	3.3E+01
Pu-240	8.3E+04	7.4E+04	5.0E+04	1.8E+05	1.9E+04	2.3E+05
Cm-243	2.1E+01	1.9E+01	1.8E+01	3.1E+00	1.5E+01	2.2E+00
Am-243	8.7E+03	7.8E+03	2.6E+03	9.3E+03	2.0E+03	1.2E+04
Pu-239	8.4E+04	7.4E+04	5.0E+04	1.8E+05	1.9E+04	2.3E+05
Pu-241	4.4E+04	3.9E+04	1.4E+00	6.9E+01	3.0E+00	2.1E+01
Am-241	2.8E+05	2.4E+05	8.7E+04	2.6E+05	6.6E+04	3.1E+05

(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 3.2 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.

(c) Where 7.0E+04 = 7.0×10^4.

buried waste by intrusion active processes are shown in Figures 3.2-1 and 3.2-2 for waste spectra 1 and 2, respectively. The peak surface accumulation for waste spectrum 1 is about 2.4 Ci/ha of trench surface, and this concentration occurs after about 90 years. For waste spectrum 2 at the western site, the peak concentration at the trench surface is about 2.0 Ci/ha and it occurs after about 100 years.

For the eastern site, the quantities of radionuclides that accumulate in soil layers above the buried waste by intrusion/active processes are illustrated in Figure 3.2-3 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. Figure 3.2-4 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. Again, the quantities shown in Figure 3.2-1 through 3.2-4 have been corrected for radioactive decay and daughter product ingrowth, with the appropriate assumed container decomposition half-time.

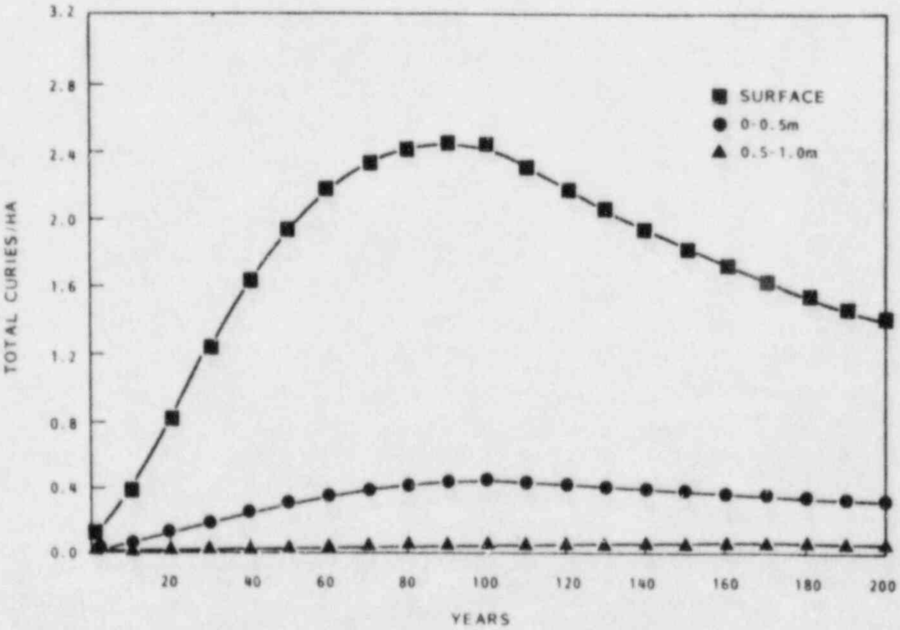

FIGURE 3.2-1. Total Ci/ha Present over 200 Years at the Western Site, Waste Spectrum 1

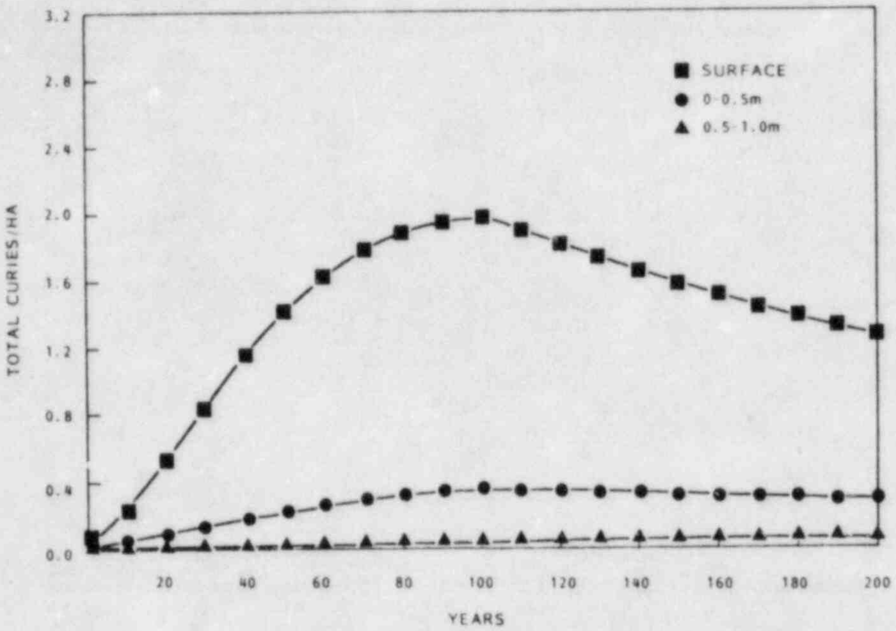

FIGURE 3.2-2. Total Ci/ha Present over 200 Years at the Western Site, Waste Spectrum 2

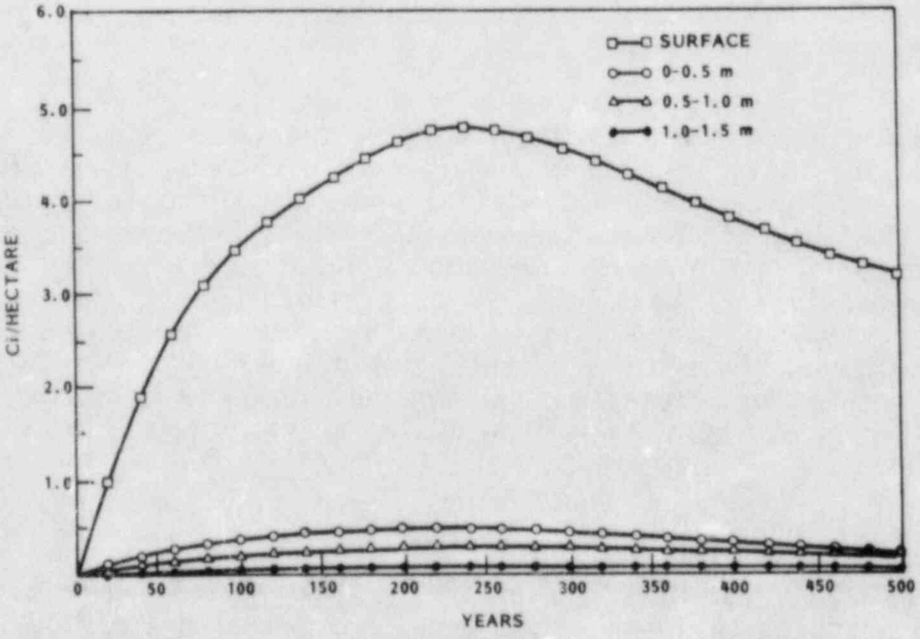

FIGURE 3.2-3. Total Ci/ha Present over 500 Years at the Eastern Site, Waste Spectrum 1

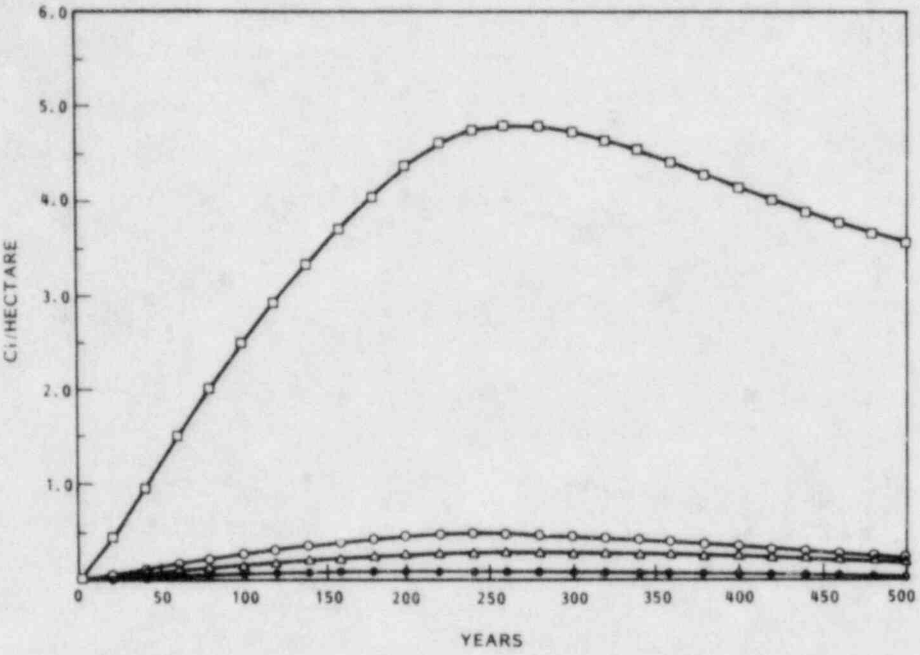

FIGURE 3.2-4. Total CI/ha Present over 500 Years at the Eastern Site, Waste Spectrum 2

3.3 DOSE CALCULATIONS

Since the mixtures of the radionuclides resulting from the human intrusion scenario and the biotic transport scenario are different, dose calculations are performed to determine the relative impacts of the two types of scenarios. By using the same environmental pathway and dose analysis model with the source terms, 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.

3.3.1 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:

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

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^* = 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.

3.3.2 Dose Calculations for Human Intrusion Scenarios

Doses to the maximum-exposed individual for the human intrusion scenario were calculated using the MAXI computer program. The surface contamination levels (Ci/m^2) for the intruder-agricultural scenario are summarized in Table 3.2-1 for waste spectra 1 and 2 for the western and eastern sites. 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 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 summarized in Table 3.3-1 for the radioactive

TABLE 3.3-1. Summary of the Maximum Annual Doses to the Maximum-Exposed Individual from the Intruder-Agriculture Scenario[a]

Waste Spectrum	Reference Site	Maximum Year[b]	Organ of Reference	Dominant Radionuclide Contributors To Dose	Dominant Exposure Pathway	Maximum Annual Organ Dose (rem)
1[c] (Past Wastes)	Western	1	Total-body	Cs-137 + D[d]	External	28
	Western	1	Bone	Cs-137 + D	External	28
2[e] (Future Wastes)	Western	1	Total-body	Cs-137 + D	External	20
	Western	1	Bone	Cs-137 + D	External	20
1[c] (Past Wastes)	Eastern	1	Total-body	Cs-137 + D	External	41
	Eastern	2	Bone	Cs-137 + D	External	42
2[e] (Future Wastes)	Eastern	2	Total-body	Cs-137 + D	External	39
	Eastern	2	Bone	Cs-137 + D	External	39

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[a] The doses are calculated over a 50-year continuous exposure period for the waste spectra 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 CLLW burial ground.

[c] Waste spectrum 1 was based on the current mixture and specific activity of CLLW radionuclides in the western and eastern United States (U. S. Nuclear Regulatory Commission (1981).

[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 CLLW mixtures and specific activities in the western and eastern United States (U. S. Nuclear Regulatory Commission 1981).

nuclides of waste spectra 1 and 2 for the reference western and eastern sites. 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. For the western site, the resulting maximum annual doses to total body are 28 rem for waste spectrum 1 and 20 rem for waste spectrum 2. For the eastern site, the maximum annual dose to bone peaks in the second year at a value of 42 rem for waste spectrum 1 and 39 rem for waste spectrum 2. Complete listings of the maximum annual doses by organ are given in the appendices of documents by McKenzie et al. (1982b; 1982c).

3.3.3 Dose Calculations for the Intrusion and Active Biotic Transport Scenarios

Doses to the maximum-exposed individual for the intrusion and active biotic transport scenario were calculated using the MAXI computer program. The surface contamination levels (pCi/m^2), resulting from this scenario are given in Table 3.2-2 for waste spectra 1 and 2 for the reference western and

TABLE 3.3-2. Summary of the Maximum Doses to the Maximally Exposed Individual from the Intrusion and Active Biotic Transport Scenario 100 Years after Closure of the Reference Western and Eastern Sites[(a)]

Waste Spectrum	Reference Site	Maximum Year[(b)]	Organ of Reference	Dominant Radionuclide Contributors To Dose	Dominant Exposure Pathway	Maximum Annual Organ Dose (rem)
1[(c)] (Past Wastes)	Western	30	Total-body	Sr-90 + D[(d)]	Ingestion	3.7
	Western	32	Bone	Sr-90 + D	Ingestion	15
2[(e)] (Future Wastes)	Western	30	Total-body	Sr-90 + D	Ingestion	3.1
	Western	32	Bone	Sr-90 + D	Ingestion	13
1[(c)] (Past Wastes)	Eastern	30	Total-body	Sr-90 + D	Ingestion	6.3
	Eastern	32	Bone	Sr-90 + D	Ingestion	26
2[(e)] (Future Wastes)	Eastern	30	Total-body	Sr-90 + D	Ingestion	4.4
	Eastern	32	Bone	Sr-90 + D	Ingestion	18

(a) The doses are calculated over a 50-year continuous exposure period.

(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 CLLW burial ground.

(c) Waste spectrum 1 was based on the current mixture and specific activity of CLLW radionuclides in the western and eastern United States (U. S. Nuclear Regulatory Commission (1981).

(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 CLLW mixtures and specific activities in the western and eastern United States (U. S. Nuclear Regulatory Commission 1981).

eastern sites. 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, 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 also 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 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 low large intestine (GI-LLI) of the maximum-exposed individual.

A summary of the resulting maximum annual doses and the year during continuous exposure in which the doses peak are given in Table 3.3-2 for the radionuclides of waste spectra 1 and 2 in reference western and eastern sites. 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. For the western site, peak bone doses are 15 rem for waste spectrum 1 and 13 rem for waste spectrum 2. For the reference eastern site, peak bone doses during continuous exposure 100 years after site closure are 26 rem for waste spectrum 1 and 18 rem for waste spectrum 2.

The year in which the peak dose occurs may not be the same year that the peak soil concentration occurs if internal exposure pathways and organs are considered. To illustrate this complex behavior, we calculated the organ dose versus time (for total body, bone, and thyroid) for the eastern site, and plotted the total concentration of radionuclides in the top 0.5 m of soil. The resulting figures are included here as Figures 3.3-1 and 3.3-2. 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.

3.3.4 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 western and eastern sites is given in Table 3.3-3. 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 ranges from 0.62 for the western site to 0.54 for the eastern site. For waste spectrum 2, the ratio of the critical organ doses for the biotic transport scenario to the human intrusion scenario ranges from 0.46 for the western site to 0.65 for the eastern site.

The doses calculated for the human intrusion scenario were based on the waste spectra for the western and eastern 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 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 doses of 20 rem for the western site and 39 rem estimated for this task indicate that the two approaches produce different, but relatively similar, results.

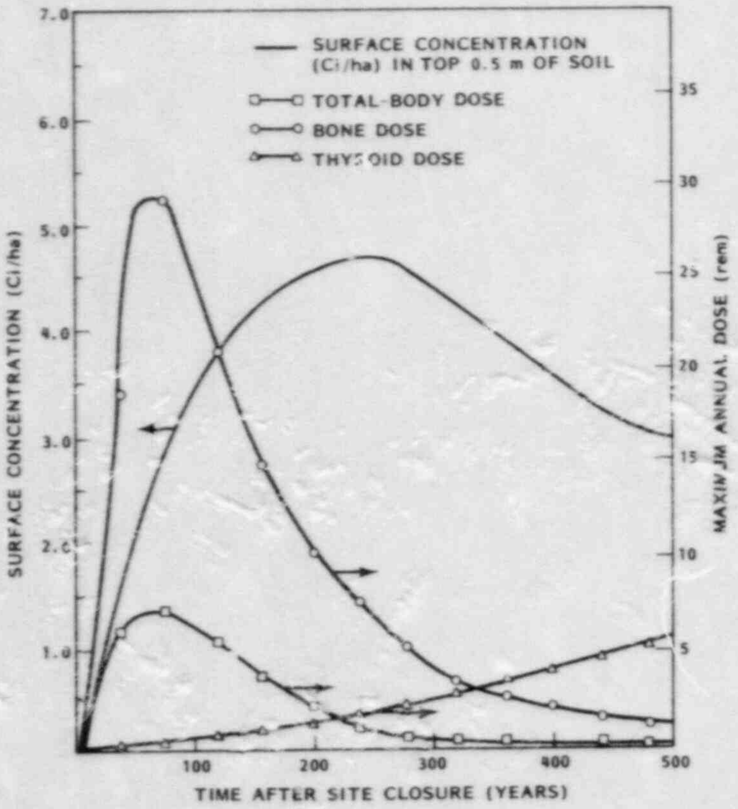

FIGURE 3.3-1. Comparison of Surface Concentration and Organ Dose over 500 Years of Biotic Transport for Waste Spectrum 1 at the Reference Eastern Site

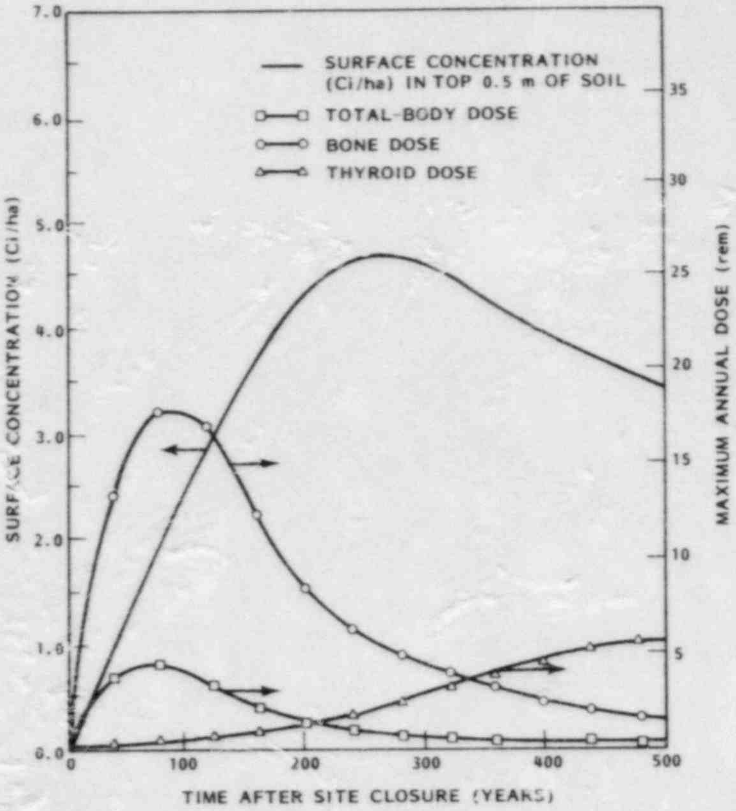

FIGURE 3.3-2. Comparison of Surface Concentration and Organ Dose over 500 Years of Biotic Transport for Waste Spectrum 2 at the Reference Eastern Site

TABLE 3.3-3. Results Comparison for Human Intrusion and Intrusion and Active Biotic Transport for the Reference Western and Eastern Sites

Waste Spectrum	Reference Site	Human Intrusion Scenario		Biotic Transport Scenario		Ratio (Biotic/Human)
		Critical Organ	Maximum Annual Dose (rem)	Critical Organ	Maximum Annual Dose (rem)	
1	Eastern	Total-body	42	Bone	26	0.62
2	Eastern	Total-body	39	Bone	18	0.46
1	Western	Total-body	28	Bone	15	0.54
2	Western	Total-body	20	Bone	13	0.65

---

[a] Doses for both scenarios are calculated for 100 years after site closure.

3.4 DISCUSSION OF RESULTS FOR PHASE I, TASK 3

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, 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 (e.g., wind and water erosion).

- 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 a sensitivity analysis is 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 commercial low-level waste disposal sites.

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 study. 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.

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4.0 DISCUSSION OF EFFORTS FOR PHASE II

The preliminary calculations in Phase I indicate that biotic transport is of potential concern in long-term performance of low-level disposal sites. In Phase II, the preliminary model will be modified and enhanced to permit state-of-the-art evaluation of the potential dose to man resulting from long-term biotic transport. Based on this evaluation, Phase II efforts within this project will determine how biotic transport considerations may be included in the regulatory process. Possible uses may include establishing maximum permissible transport criteria for given pathways, identifying which pathways are relevant for which types of nuclear waste disposal facilities and procedures, and recommending methods for their inclusions in site evaluations. A description of the specific tasks that are underway in Phase II is given in the following sections.

4.1 TASK 1: BIOTIC TRANSPORT MODELING

The objective of this task is to develop improved models that can better predict the quantities of radionuclides transported by biotic processes. The resulting model will be used to provide a more accurate prediction of the dose to man than the "order of magnitude" estimates provided in Phase I. Thus, in this task, we are refining and modifying the model used to make these biotic transport estimates. In addition to modifying the model, we are:

- reviewing and attempting to improve the exponential decay model currently used to represent CLLW package/waste form decay,
- assessing the assumption of uniform biological availability with respect to package decay, and
- attempting to improve the simulation of the intruder-agriculture scenario used as a comparison standard that can indicate the relative importance of biotic transport.

Other efforts in this task are being focused on using a sensitivity analysis to determine which parameters control the model predictions for the significant radionuclides. The intent of this effort will be to help determine how best to improve the model and its results. To the degree that the model truly represents biotic transport, the sensitivity analysis will also provide an indication of the importance of individual biotic pathways.

In this task, the reference western and eastern site descriptions and data will be replaced with actual data from operating sites. Data are needed on site areas, trench configurations, biological communities, and radionuclide inventories. In addition, data from four additional regions where future CLLW sites may be established will be collected and reviewed.

4.2 TASK 2: TECHNOLOGY TRANSFER

The BIOPORT computer program is the computer implementation of the model developed in this project for accounting for the biotic transport of radionuclides from a commercial low-level waste burial ground. Comparative dose estimates are made for the exposure scenarios using the MAXI computer program. The purpose of this task will be to provide the NRC with a copy of the entire computational package with sufficient documentation so that NRC staff members may use it. The computer program documentation will include a description of the use of the computer programs, as well as a description of the theoretical basis of the programs and their applications and operations.

The computer programming efforts will conform to FORTRAN 77 and applicable sections of ANSI Standard X3.9-1978, FIPS 38 3-12-78, and ANSI Standard N-413. To provide verification of correct operation of the computer programs, both the input and output will be presented for a set of five sample problems selected with NRC approval. The users' manual will contain sections on:

- theoretical basis of the overall model and modifications,
- practical considerations and limitations for application,
- technical information for running the computer program,
- definition of program variables,
- description and accession of data sets,
- example problems for various program operations,
- a program logic flow chart and listing, and
- references.

Finally, a one-day short course will be designed and presented to NRC staff. In this course we will fully describe the points above; we will also examine how input should be prepared, how output should be interpreted, and how data sets should be accessed and modified.

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Licensing and regulation of commercial low-level waste (CLLW) burial facilities require that anticipated risks associated with burial sites be evaluated for the life of the facility. This work reviewed the existing capability to evaluate dose to man resulting from the potential redistribution of buried radionuclides by plants and animals. Through biotic transport, radionuclides can be moved to locations where they can enter exposure pathways to man. We found that predictive models currently in use did not address the long-term risks resulting from the cumulative transport of radionuclides. Although reports in the literature confirm that biotic transport phenomena are common, assessments routinely ignore the associated risks or dismiss them as insignificant. To determine the potential impacts of biotic transport, we made order-of-magnitude estimates of the dose to man for biotic transport processes at reference arid and humid CLLW disposal sites. Estimated doses to site residents after assumed loss of institutional control were comparable to dose estimates for the intruder-agricultural scenario defined in the DEIS for 10 CFR 61 (NRC). The reported lack of potential importance of biotic transport at low-level waste sites in earlier assessment studies is not confirmed by order of magnitude estimates presented in this study.

17. KEY WORDS AND DOCUMENT ANALYSIS

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