NUREG/CR-2675
PNL-4241
Vol. 1

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

A Report on Tasks 1 and 2 of Phase I

Prepared by D. H. McKenzie, L. L. Cadwell, C. E. Cushing, Jr., R. Harty,
W. E. Kennedy, Jr., M. A. Simmons, J. K. Soldat, B. Swartzman

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
   Washington, DC 20555
2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
   Washington, DC 20555
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

GPO Printed copy price: $5.00

NUREG/CR-2675
PNL-4241
Vol. 1
RW

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

A Report on Tasks 1 and 2 of Phase I

Manuscript Completed: April 1982
Date Published: July 1982

Prepared by
D. H. McKenzie, L. L. Cadwell, C. E. Cushing, Jr., R. Harty,
W. E. Kennedy, Jr., M. A. Simmons, J. K. Soldat, G. Swartzman

Pacific Northwest Laboratory
Richland, WA 99352

Prepared for
Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN B2377

ABSTRACT

The purpose of the work reported here was to evaluate the relevance of biotic transport to the assessment of impacts and licensing of low-level waste disposal sites. Available computer models and their recent applications at low-level waste disposal sites are considered. Biotic transport mechanisms and processes for both terrestrial and aquatic systems are presented with examples from existing waste disposal sites. Following a proposed system for ranking radionuclides by their potential for biotic transport, recommendations for completing Phase I research are presented. To evaluate the long-term importance of biotic transport at low-level waste sites, scenarios for biotic pathways and mechanisms need to be developed. Scenarios should begin with a description of the waste form and should include a description of biotic processes and mechanisms, approximations of the magnitude of materials transported, and a linkage to processes or mechanisms in existing models. Once these scenarios are in place, existing models could be used to evaluate impacts resulting from biotic transport and to assess the relevance to site selection and licensing of low-level waste disposal sites.

Relevance of Biotic Paths to the Regulation of Nuclear Waste Disposal

Summary of Tasks I and II

Alternatives for licensing and regulating low-level waste burial sites need to be selected on the basis of reasonable evaluations of risk. With regard to low-level sites, biotic transport processes must be evaluated along with other transport processes (e.g. groundwater, agricultural food chains) if the consequences of alternative courses of action are to be understood. Biotic transport (amounts and rates of radionuclide transport by biota) at waste facilities is poorly understood when compared to current understanding of routes and movements of radionuclides through agricultural food chains.

This report concludes work on Tasks I and II, Phase I of this research program. Our objective was to assess current biotic transport modeling. Our efforts have focused on evaluating the relevance of biotic transport to the assessment of impacts of waste disposal on humans and their environment. This review considers available computer models and the applications of models at low-level waste disposal sites. An identification and review of biotic transport mechanisms and processes for both terrestrial and aquatic systems is provided. Recommendations and rationale for tasks required to complete Phase I are included. The final report for Phase I will contain: a) a critical review of available modeling techniques; b) an assessment of the possible significance of biotic transport of radionuclides from low-level waste disposal sites to man; and c) if appropriate, a summary of additional investigations needed to apply biotic transport modeling to regulatory concerns effectively.

Review of Models

A review of transport and radiation exposure pathway models revealed that these models consider only atmospheric and surface/ground water transport mechanisms; none directly considers biotic transport. These models were found to contain essentially the same methods and equations. A primary difference among these models was the scenario addressed by the impact assessment study. None of these models considers such long-term impacts as the integrity of the buried waste containers, nor the increases in accessibility of waste resulting from biotic mechanisms and processes. Although exposure pathways models have been developed to calculate radionuclide concentrations in human food sources, no attempt has been made to model radionuclide transport to these food chains or to man via biotic mechanisms or processes.

Biotic Transport in Terrestrial Systems

Review of literature and site studies revealed that no in-depth studies of radionuclide movement via biota have been conducted for waste disposal sites, although a number of specific examples of biotic transport have been observed. Three biotic transport mechanisms, which may have been involved in these examples of radionuclide transport at low-level waste sites, are transport enhancement, intrusion and active transport, and secondary transport. Transport enhancement occurs when the biota modify the waste site or the waste itself and thus increases the potential for radionuclide transport. Burrowing mammals and invertebrates, for example, construct tunnels that enhance exchange of gases and access of surface water to the waste. Intrusion and active transport occur when biota (both plants and animals) penetrate waste zones and effect a horizontal and vertical redistribution of waste materials. In secondary transport, radionuclides are available to biota for horizontal displacement only after they have been mobilized by other processes. Radionuclides, for example, may reach surface waters via groundwater transport and then be transported by insects, plants or animals using the contaminated water.

Biotic Transport in Aquatic Systems

Radionuclides from low-level waste sites can reach surface water bodies directly (through water flows or leaching) or indirectly (through biota). While considerable information is available on radionuclide cycling in aquatic food webs, no data are available that indicate biotic transport in aquatic ecosystems. Cases have been documented of organisms transporting radionuclides from contaminated aquatic environments; this could also occur at low-level waste sites as well.

Under present conditions, the likelihood of significant amounts of radionuclides reaching aquatic surface sites is remote. If radionuclides do reach surface waters, their cycling patterns (in food webs) will be the same as if they had been released from other sources. Current models for predicting dose should be adequate to account for movement of radionuclides by these pathways.

There is a need to assess potential for getting material from waste site to surface water where it can enter aquatic food chains.

Classification of Potential Biotic Transport

A classification scheme for assessing radionuclides with regard to their potential for biotic transport was developed in conjunction with the review of biotic transport. Results of a preliminary application of this scheme to a group of radionuclides indicated general agreement with other rankings, which were generally based on a hazard index. Refinement of the six criteria and the information base is needed to rank radionuclides on their potential f[illegible]iotic transport.

Efforts Needed to Complete Phase I

The next step toward completion of Phase I should begin with the formulation of scenarios for each of the biotic pathways and mechanisms identified in Task I. Each scenario should begin with a description of the waste material (its form). It should contain: a description of the biotic processes and mechanisms, first order approximations of the magnitude of materials transported, and a linkage to processes or mechanisms in existing models. The existing models could then be used to predict the resulting impact under such a scenario. The calculated results could then be compared to the results for the existing scenarios. This comparison process would then form the basis for an assessment of the relative significance of biotic transport.

CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

This report is concerned with one aspect of regulations for and management of low-level shallow waste burial sites. Concern for the impacts from human exposure to radioactivity has resulted in a series of regulatory guidlines, environmental assessments and management practices and tools. The need to consider and integrate a large number of processes and mechanisms that may contribute to radiation dose has resulted in a number of computer programs or codes to make the required calculations. Additionally, evaluations of radionuclide behavior and movements for extended time periods of up to 500 years have been needed.

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 Adams et al. 1978, and typically the current application practice, is to assume that biotic pathways need not be evaluated by rigorous techniques, i.e. modeling. This report assesses the evidence behind these two statements and evaluates their relevancy to low-level waste management.

Radiation exposure pathways by which radionuclides may move from low-level shallow waste burial sites and ultimately contribute to the human radiation dose generally fall within one of three broad categories. The first category, and the one frequently evaluated by model assessment, is the direct agricultural pathway. Typically, two basic scenarios have been constructed to evaluate agricultural pathways. These scenarios are based on assumptions that allow the waste to "contact" domestic crops. In the first scenario, future generations are assumed to inhabit a waste disposal site as a result of loss of institutional control (LOIC), usually taken to be 100-300 years after waste disposal or site license termination. People are assumed to grow crops directly over the waste trenches, and plant root intrusion provides a mechanism for human exposure to the radionuclide wastes. In the second scenario, radionuclide contamination of crop plants is assumed to result from the use of contaminated water for irrigation (Schreckhise 1980). Leaching of contaminants from low-level waste burial sites into ground or surface waters permits this pathway to become established. The contaminated water is then used at some location remote from the burial site.

A second category of radiation exposure pathway considers the ingestion of wildlife and noncultivated plant species. Though similar to the agricultural pathway, this category differs in several regards. Wildlife pathways may be more immediate as the extended time period for LOIC or migration of ground water implied for agricultural pathways is not required. Game animals harvested by man can move onto managed burial sites and incorporate contaminants into their tissues. Moreover, many game animals are highly mobile and may carry contaminants to remote offsite locations. In contrast to agricultural pathways, no human activity, other than harvesting the game or plant products, is required to complete the food chain to man. Quantities of edible wildlife products that are available for utilization by man, however, are several orders of magnitude smaller than those from agriculture.

Numerous examples of radionuclide incorporation into fish, game and noncultivated plant tissues from defense waste management sites have been identified. The quantities of radionuclides transported from low-level defense waste management sites and the potential dose to man from ingestion of wildlife have been calculated in some cases (Cadwell et al. 1979; Emery et al. 1981; Price et al. 1981), but the wildlife pathway is frequently not considered in dose assessment practice.

The third category for radiation exposure, and the one that we are concerned with in this report, includes biotic transport pathways. In contrast to the two categories mentioned earlier, these pathways are usually indirect, lengthy and in general much less well understood or measured. Although the radionuclides may eventually reach agricultural products and wildlife (as well as cycling through standard biogeochemical cycles), the quantities transported over time under active site maintenance programs are likely to be small. Thus, it is these indirect pathways and to a somewhat lesser extent, wildlife pathways, that are routinely assumed to be negligible and therefore omitted from consideration in dose assessment practice.

In-depth studies of radionuclide movement through the biota associated with commercial low-level waste 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 which transport radionuclides. The inferences for biotic transport potential are relatively clear. What is not known, and has not been assessed, is the magnitude of the transport over longer times (up to 500 years) and the potential consequences associated with it.

This report contains a technical assessment of the techniques used to assess the contribution to human radiation dose from biotic transport mechanisms and processes. This report provides an evaluation of the relevance of biotic transport in the assessment of the impact of waste disposal on man and his environment. This report provides a critical review of the role of modeling in evaluating biotic transport, from the standpoint of both current applications and future models. Evidence of the occurrence of biotic transport of radionuclides is provided from low-level waste management sites.

Section 2 of this report contains a review of current information relating to low-level radioactive waste management. A review and comparison of commonly used radiation dose pathway analysis models is followed by a review of current low-level radioactive waste management literature. Sections 3 and 4 contain reviews of biotic transport in terrestrial and aquatic systems, respectively. In Section 5, a preliminary classification of radionuclides by potential biotic transport is presented and compared with other radionuclide classification results. Finally, Section 6 contains recommendations for establishing the potential magnitude of biotic transport and its role in low-level radioactive waste management decisions.

1.1 REFERENCES

Cadwell, L. L., R. G. Schreckhise and R. E. Fitzner. 1979. *Cesium-137 in Coots on Hanford Waste Ponds: Contribution to Population Dose and Offsite Transport Estimates*. PNL-SA-7167, Pacific Northwest Laboratory, Richland, Washington.

Emery, R. M., D. C. Klopfer, D. A. Baker and J. K. Soldat. 1981. Potential radiation dose from eating fish exposed to actinide contamination. *Health Phys*. 40:493-510.

Price, K. R., L. L. Cadwell, R. G. Schreckhise and F. P. Brauer. 1981. *Iodine-129 in Forage and Deer on the Hanford Site and Other Pacific Northwest Locations*. PNL-3357, Pacific Northwest Laboratory, Richland, Washington.

Schreckhise, R. G. 1980. *Simulation of the Long-Term Accumulation of Radiocontaminants in Crop Plants*. PNL-2636, Pacific Northwest Laboratory, Richland, Washington.

2.0 REVIEW OF BIOTIC TRANSPORT CONSIDERATIONS IN COMMERCIAL LOW-LEVEL WASTE MANAGEMENT

Commercial low-level waste (LLW) burial grounds are located primarily on the basis of regional requirements for radioactive waste disposal. Final siting decisions rely on many considerations, though hydrogeologic and economic concerns are often most important. Existing information regarding biotic transport was reviewed and evaluated to determine the potential importance of biotic transport on siting and operating commercial LLW burial grounds. This included a review of biotic pathway considerations in recently published LLW management reports.

In this section definitions are provided for concepts used in this report. Radionuclide transport and radiation exposure pathway models are then reviewed and compared. After a critical look at recent studies of low-level waste management, the issue of how to use biotic transport models in low-level waste management is addressed.

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 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.

Atmospheric Transport. Physical movement of material through the action of the wind and/or precipitation. Wind resuspension is the primary means of atmospheric transport of interest in this study.

Ground-Water Transport. Movement of soluble radioactive materials by ground water. The primary means of ground-water transport are overland flow (the "bathtub" effect) and mass transport through the saturated zone.

Biotic Transport. Actions of plants or animals that transport radioactive materials from a LLW burial ground to a location where they 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 LLW 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. 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 AND RADIATION EXPOSURE PATHWAY MODELS

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; and Science Applications, Inc. 1979). The review resulted in a list of 23 computer programs for further evaluation (Table 2.1). After the computer programs were identified, they were classified and compared as discussed in the following sections.

2.2.1 Identification of Computer Programs

The computer programs identified for review (Table 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 Kaye 1971). Because the development of RAGTIME is 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

TABLE 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)

---

*Designates a model chosen for extensive review

Reasons for Removal from Further Consideration

1. Redundant, i.e. capabilities available in other programs or precursor or descendent of program reviewed
2. Incomplete documentation
3. Overly detailed in analysis or parameters not all available.

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 1979).

Some computer programs weren't considered because they were redundant. This category included computer programs such as 2BPUFF (Crawford 1966), whose information is contained in other computer programs. Computer programs were also not included if sufficient code documentation did not yet 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 their equations could not easily be changed to calculate concentration as opposed to dose. These included AIRWAY (Rider 1979) and BIOTRAN (Gallegos et al. 1980).

2.2.2 Model Classification and Comparison

Table 2.2 contains an overview of the nine computer programs which were selected for extensive review. The computer programs were written to calculate the dose received by individual persons and/or population groups from a release of radionuclides to the environment. The sources of the radionuclides addressed by the programs include normal and accidental releases to air and surface water from nuclear facilities and fallout of debris from nuclear testing. The releases were categorized as either acute or chronic. The models were geographically nonspecific with the exception of RVRDOS (Martin et al. 1976), which was specific to the Mississippi River Basin.

The programs were classified in terms of their transport mechanisms. The programs listed in Table 2.2 which have atmospheric releases or fallout as a source of radionuclides (AIRDOS-EPA and TERMOD) consider deposition

Table 2.2. Overview of Computer Program Elements

Computer Program	AIRDOS-EPA	AQUAMAN	ARRRG	BIODOSE	CRITR	FOOD	MILDOS	RVRDOS	TERMOD
Source of Radiation	Atmospheric Release	Aqueous Release	Aqueous Release	Aqueous Release	Aqueous	Atmospheric or Aqueous	Uranium Mill Facilities	Aqueous Stream	Fallout
Dose Commitment Factor	Annual	50 yr based on 1 yr exposure	Annual	Annual	Annual	Annual	50 yr based on 1 yr exp. or 100 yr env. dose comm.	Annual	None %30 yr intake
Dose to									
• Individual	X	X	X	X	X	X	X	X	X
• Population	X		X	X		X	X	X	
Release Type									
• Chronic	X	X	X	X	X	X	X	X	X
• Acute		X	X			X			X
Geography	General	General	General	General	General	General	General	Mississippi River Basin	General
Radionuclide Transport									
Atmospheric	X					X	X		
Deposition Dry	X					X	X		X
Wet	X								
Resuspension							X		
Surface Water		X	X		X			X	
Groundwater									
Sedimentation				X					
Irrigation				X		X			
Drinking Water		X	X					X	
External Exposure Pathways									
Air Exposure	X						X		
Ground Exposure	X			X			X		
Water Exposure	X	X	X	X				X	
Shoreline-Sediment Exposure									
Internal Exposure Pathways									
Ingestion	X	X	X	X	X	X	X	X	X
Inhalation	X						X		
Number of Nuclides	36	56 (20/run)	280 (100/run)	36	136	280 (100/run)	10	20	75

Table 2.2. Overview of Computer Program Elements

Computer Program	AIRDOS-EPA	AQUAMAN	ARRRG	BIODOSE	CRITR	FOOD	MILDOS	RVRDOS	TERMOD
Ingrowth of Daughters Calculated	X (not in veg.)	X	X		X	X	X	X	
Decay	X		X	X	X	X		X	X
Separate Treatment of									
• H-3	X					X			X
• C-14	X					X			
Taxa List									
Aquatic Organisms									
• Algae			X		X				
• Crustaceans			X	X	X				
• Molluscs			X	X	X				
• Fish		X	X	X	X			X	
• Secondary Org.					X				
Terrestrial Plants									
• General Produce	X								
• Leafy Veg	X			X		X			
• Other Above Ground Vegetables				X		X	X		X
• Potatoes				X		X	X		
• Other Root Veg.				X		X	X		
• Berries				X		X			
• Melons				X		X			
• Orchard Fruit				X		X			
• Wheat				X		X			
• Other Grains				X		X			
• Pasture Grass	X			X		X	X		X
• Hay							X		
Terrestrial Animals									
• Milk Cow						X			X
• Beef Cattle	X					X	X		X
• Pork						X			
• Poultry						X			
• Eggs									
• General Agr.	X								

exposure pathways and exposure pathways through terrestrial biota. The programs that address the dose received from an aqueous radionuclide release, such as AQUAMAN (Shaeffer and Etnier 1979), ARRRG, CRITR and RVRDOS, use pathways including surface water, drinking water and aquatic organisms. Other programs are more complex. BIODOSE (Duffy and Bogar 1980) considers not only aqueous sources, but also concentrations of radionuclides in terrestrial plants grown in soil irrigated with contaminated water. FOOD is the only program analyzed that considers both atmospheric and aqueous sources of radionuclides in terrestrial foodstuffs. FOOD can be used to calculate the concentration of radionuclides only in terrestrial biota; however, it does consider the irrigation of crops by contaminated water and the ingestion of contaminated drinking water by animals. The MILDOS program was designed for use with effluents from uranium milling facilities and tailings piles. MILDOS considers transport through environment by atmospheric release and/or suspension and subsequent deposition on to plant and ground surfaces.

The programs vary widely in their treatment of sources of external exposure, including air, ground, water, and shoreline sediments. TERMOD does not calculate external exposure, while the other programs contain one or more external exposure pathways.

Inhalation and ingestion are the two basic internal exposure pathways. The programs that consider ingestion address both people and animals. Those that consider inhalation address people only because of the lack of data for the behavior of inhaled radionuclides in animals.

The total number of radionuclides that are considered in each program are listed in the Table 2.2. The radionuclides and their associated parameters are usually stored in a program library. The number in parentheses denotes the number of radionuclides that can be considered in a single computer run; these values range from 10 to 280.

Miscellaneous items, such as the consideration of daughter radionuclide ingrowth, the calculation of radioactive decay, and separate treatment of H-3 and C-14 are noted.

A list of the organisms considered by the aquatic and terrestrial pathways is given in Table 2.2. Some programs (e.g. TERMOD) use general categories for ingestion by man, such as aboveground vegetation, pasture grass, beef and milk, while other programs (e.g. FOOD) use up to 14 different categories for vegetation. CRITR calculates internal dose to four groups of primary aquatic organisms and up to six secondary semi-aquatic organisms such as beaver, heron, and muskrat. With the exception of CRITR, models consider only agriculturally oriented biota.

2.2.3 Model Applicability

The radionuclide transport and radiation exposure pathway computer programs listed in Table 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 LLW trenches or the increase in accessibility of the buried wastes resulting from biotic mechanisms.

2.3 RECENT LOW-LEVEL WASTE MANAGEMENT STUDIES

Recent studies on LLW disposal reviewed here include discussions of impact analysis, waste classification, environmental assessment, and decommissioning. No studies were found, however, that specifically address biotic transport mechanisms. Studies reviewed here utilize environmental models designed to evaluate transport by biota not directly related to the human food chain. The following sections contain brief discussions of the findings related to biotic transport considerations in recent LLW reports.

2.3.1 System Analysis of Shallow Land Burial

A user's manual for the BURYIT computer program, prepared by Lester et al. (1981) of Science Applications, Inc., is a systems analysis tool for comparing the impacts of operational and siting alternatives for shallow land burial on total public radiation dose. The program performs one-dimensional radionuclide transport calculations for air and water pathways. Integrated 50-year population or individual dose commitments are calculated for the major release scenarios from shallow land burial sites.

For all of the scenarios considered by the computer program, initial transport to the biosphere occurs via air or water. No direct biotic transport mechanisms from the waste trench to the biosphere are defined. Once radionuclides reach the environment, they may be transported by secondary mechanisms through atmospheric, terrestrial and aquatic media. The media involved are those considered in the traditional food chain pathways.

During the period of unrestricted public use after site closure, anthropogenic events are included and regarded as potentially important. Anthropogenic events introduce new exposure pathways resulting from farming, well digging, excavation, and resource (scrap) recovery.

Apart from food chain modeling after radionuclide migration, no biotic transport mechanisms are considered; no attempt is made to quantify or model the potential impacts associated with biotic transport.

2.3.2 A Classification System for Radioactive Waste Disposal - What Waste Goes Where?

A method for classifying radioactive wastes to aid in adequate disposal is described by Adam and Rogers (1978). The broad objectives of the classification system are: to classify radioactive wastes by their requirements for safe disposal; to address the concerns of the public; and to avoid an undue burden on those affected by the implementation of the system. Classification aids in selection of the most appropriate means for disposal of various types of radioactive wastes. Disposal actions may be placed in one of three categories: 1) direct discharge to the biosphere (similar to disposal of trash), 2) confinement in a controlled manner resulting in predictably low release rates, and 3) total isolation from the biosphere so that inadvertent intrusion by man or other significant release events are highly unlikely.

To meet waste disposal objectives, Adam and Rogers (1978) describe a method for conducting a comparative risk analysis. This method relies on available technology for estimating the potential public health risks associated with radioactive waste disposal. Human exposure events include human intrusion into the disposal site as well as other events during which radioactive material is transported offsite by air or water. The authors state that:

> "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)

Although the intent of the risk analysis method is to establish a consistent set of events for comparative analysis, no attempt is made to quantify the potential impacts of biotic transport mechanisms.

2.3.3 A Radioactive Waste Disposal Classification System

Supplemental information on the waste classification system described by Adam and Rogers (1978) is provided by Rogers (1979). The objectives and methods are the same as those already discussed in a review of the document by Adam and Rogers (1978; see previous section). The risk analysis methods (i.e. risk equals consequence times probability of occurrence) are once again stated. Again, no attempt is made to quantify the potential impacts of biotic transport mechanisms.

2.3.4 Draft Environmental Impact Statement on 10CFR Part 61 "Licensing Requirements for Land Disposal of Radioactive Waste"

As part of the National Environmental Policy Act of 1969 (NEPA), the U. S. Nuclear Regulatory Commission has issued a draft environmental impact statement (EIS) on the proposed new regulation 10CFR61 (U.S. NRC 1981). In this draft EIS, the NRC demonstrates the decision processes applied to the development of new regulations. The impacts associated with low-level waste disposal are estimated for a base case and several alternatives; estimated impacts principally involve long-term radiological exposures and costs. The authors state that long-term exposure pathways could involve human intrusion, potential leaching and groundwater transport, dispersion by plants and animals, long-term erosion of the overburden, air and water transport, and gaseous decomposition.

Plant and animal intrusion and dispersion of buried low-level wastes are included in a discussion of other long-term pathways. The draft EIS contains the following statement:

> "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)

The authors make no attempt to quantify or model the potential impacts of biotic transport mechanisms beyond these brief statements.

2.3.5 Environmental Assessment Model for Shallow Land Disposal of Low-Level Radioactive Wastes: Interim Report

Little et al. (1981) report on an interim version of the PRESTO (Prediction of Radiation Effects from Shallow Trench Operations) computer program. This program is being developed for the U. S. Environmental Protection Agency to predict health impacts to static population groups over a 1000-year period following burial operations. Data are being developed for three specific sites: Barnwell, South Carolina; Beatty, Nevada; and West Valley, New York. The models in the computer program are intended to assess radionuclide transport, resulting exposures, and health impacts. The basic exposure scenarios considered in the PRESTO models include: routine operations with routine spillage; human intrusion; site reclamation (farming); and atmospheric suspension of radionuclides from an eroded trench. No mention is made about the potential impacts of biotic transport mechanisms during the 1000-year analysis period, and no attempts are made to model or otherwise quantify them.

2.3.6 Technology, Safety and Costs of Decommissioning a Reference Low-Level Waste Burial Ground

Murphy and Holter (1980) provide safety and cost information for the conceptual decommissioning of commercial low-level waste burial grounds. They consider both an arid western site and a humid eastern site as the location for reference facilities. Typical hydrology, climate, and geology conditions of arid western and humid eastern locations are used in the conceptual analysis.

The method for determining the release conditions for the decommissioned burial grounds is based on the concept of an allowable annual dose to a maximum-exposed individual. Radiation dose factors from the DACRIN (Houston et al. 1976) and the ARRRG and FOOD (Napier et al. 1980) computer programs are used to determine the maximum annual dose. This analysis considers four types of release mechanisms that can act on the buried waste: geomorphological, hydrological, anthropological, and biological.

The major geomorphological force of concern is erosion of the waste trench covers, which would expose the waste to near surface human activities such as farming.

Hydrological release mechanisms include direct contact of waste by ground water, rain water percolation, and overland flow of water from nearby surface streams. Again, after waste migration, exposure pathways to people are considered.

Direct excavation into buried radioactive waste is defined as the most significant anthropological event which could result in exposure pathways to people. During excavation, direct exposure to penetrating radiation from the waste and inhalation of airborne radioactivity can occur.

Direct root uptake of radionuclides by farm products is the only biological release mechanism considered; the authors do not consider biotic transport mechanisms. In fact, Volume 1 of the final report contains the statement:

> "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)

No attempt was made to model or determine the potential magnitude of biotic transport as a means of dispersing radioactive material.

2.4 THE POTENTIAL ROLE OF BIOTIC TRANSPORT MODELS

The impacts of plant and animal actions at low-level waste burial grounds may be associated with: 1) degradation of waste forms or trenches to permit enhanced transport of waste by air or water and 2) direct uptake or transport by species that intrude into the waste zone. The following sections contain discussions of potential applications for biotic transport modeling.

2.4.1 Model Applications

The long-term behavior of material buried at LLW burial grounds is a topic of prime concern in site-specific environmental assessments. Typically, the radiotoxicity of low-level wastes is evaluated for up to about 500 years. Such a time frame is valid since most radionuclides in low-level wastes have relatively short half-lives. However, some radionuclides disposed of in LLW burial grounds, such as C-14, Ni-59, Tc-99, I-129, transuranic radionuclides, and radionuclides in the uranium decay chain, have half-lives much longer than 500 years. In an attempt to account for the long-term behavior of these radionuclides in the environment adequately, much effort has been devoted to modeling long-term ground-water migrations. However, no corresponding effort has been made to account for the potential long-term impacts of plants and animals on either the wastes, waste containers, or the trench material overlying the wastes.

Actions of plants or animals on the waste forms or trenches may enhance radionuclide transport by air or water. For example, plant or tree roots may penetrate the overburden and eventually permit direct rainwater contact with the waste zone. Additionally, organisms that accelerate the decomposition of certain disposal containers and forms of waste may be present in the waste trenches, making the waste more easily transported by ground water.

In the next phase of this project, modeling efforts will be focused on these and other biotic mechanisms that could enhance long-term radionuclide transport.

At this time, it is difficult to estimate the impacts of biotic transport mechanisms adequately, since biotic transport mechanisms have not been modeled or quantified. Models need to be developed to estimate the quantities and concentrations of materials directly removed from burial sites by the actions of plants and animals. Since most of the plant and animal species of concern here are not directly related to the food chain, additional formulations will be required to link the new model to the food chain computer programs.

While the magnitude and type of potential biotic transport problems may be highly site-specific, it is inappropriate to continue ignoring the potential long-term impacts of biotic transport. Modeling efforts will help determine the importance of biotic transport relative to other long-term mechanisms (such as ground-water transport) currently addressed in environmental impact assessments.

2.4.2 Assessment Scenario/Model Interface

When conducting environmental impact assessments, exposure scenarios and their interface with the assessment models used must be carefully established. In the past, long-term scenarios for surface erosion, ground-water transport and human intrusion have been directly coupled with dose-to-man pathway models. While this procedure may result in a convenient assessment method, it ignores the contributions to dose from secondary pathways such as biotic transport. It has never been proven that the impacts of biotic transport are insigificant for long-term exposure scenario analysis.

Additionally, the combined uncertainties in the parameters selected for existing long-term analyses can result in large uncertainties in results. Such uncertainties are rarely quantified and reported with the modeling results.

2.5. REFERENCES

Adam, J. A. and V. C. Rogers. 1978. A Classification System for Radioactive Waste Disposal -- What Waste Goes Where? NUREG-0456, FBDU-224-10. Office of Nuclear Material Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D. C.

Booth, R. S. and S. V. Kaye. 1971. Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment. ORNL-TM-3135, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Brenchley, D. L., J. K. Soldat, J. A. McNese, E. C. Watson. 1977. Environmental Assessment Methodology for the Nuclear Fuel Cycle. BNWL-2219, Pacific Northwest Laboratory, Richland, Washington.

Crawford, J. V. 1966. A Computer Program for Calculating the Atmospheric Dispersion of Large Clouds. UCRL-50179, University of California, Lawrence Livermore Laboratories, Livermore, California.

Duffy, J. J. and G. P. Bogar. 1980. User's Manual for Biosphere and Dose Simulation Program (BIODOSE). UCRL-15188, Analytic Sciences Corp., Reading, Massachusetts.

Fletcher, J. F. and W. L. Dotson. 1971. HERMES: A Digital Computer Code for Estimating Regional Radiological Effects from the Nuclear Power Industry. HEDL-TME-71-168. Hanford Engineering Development Laboratory, Richland, Washington.

Gallegos, A. F., B. J. Garcia, C. M. Sutton. 1980. Documentation of TRU Biological Transport Model (BIOTRAN). LA-8213-MS, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

Hoffman, F. O., C. W. Miller, D. L. Shaeffer, C. T. Garten, Jr., R. W. Shor, J. T. Ensminger. 1977. A Compilation of Documented Computer Codes Applicable to Environmental Assessment of Radioactivity Releases. ORNL/TM-5830, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Houston, J. R., D. L. Strenge and E. C. Watson. 1976. DACRIN -- A Computer Program for Calculating Organ Dose from Acute or Chronic Radionuclide Inhalation. BNWL-B-389, UC-41, Pacific Northwest Laboratory, Richland, Washington.

Lester, D., D. Buckley, S. Donelson, V. Dura, M. Hecht, W. Horton, T. Nakai, T. Pasternak, L. Robertson, R. Stula, J. Stoddard. 1981. Systems Analysis of Shallow Land Burial. NUREG/CR-1963, Prepared for the U. S. Nuclear Regulatory Commission by Science Applications, Inc., La Jolla, California.

Little, C. A., D. E. Fields, C. J. Emerson and G. Hiromoto. 1981. Environmental Assessment Model for Shallow-Land Disposal of Low-Level Radioactive Wastes: Interim Report. ORNL/TM-7943. Prepared for the U. S. Environmental Protection Agency by Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Martin, J. A., JR., C. Robbins, C. B. Nelson, R. D. Cousins, Jr., M. A. Culliton. 1976. A Computer Code (RVRDOS) to Calculate Population Doses from Radioactive Liquid Effluents and an Application to Nuclear Power Reactors on the Mississippi River Basin. ORP/EAD-76-4, U. S. Environmental Protection Agency, Office of Radiation Programs, Washington, D. C.

Miller, C. W. 1978. The Evaluation of Models Used for the Assessment of Radionuclide Releases to the Environment. ORNL-5382, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Momeni, M. H., Y. Yuan, and A. J. Zielen. 1979. The Uranium Dispersion and Dosimetry (UDAD) Code. NUREG/CR-0553, ANL/ES-72, Argonne National Laboratory, Argonne, Illinois.

Moore, R. E. 1977. The Airdos-II Computer Code for Estimating Radiation Dose to Man from Airborne Radionuclides in Areas Surrounding Nuclear Facilities. ORNL-5245, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Moore, R. E., C. F. Baes III, L. M. McDowell-Boyer, A. P. Watson, F. O. Hoffman, J. C. Pleasant, C. W. Miller. 1979. AIRDOS-EPA: A Computerized Methodology for Estimating Environmental Concentrations and Dose to Man from Airborne Releases of Radionuclides. ORNL-5532, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Mosier, J. E., J. R. Fowler, C. J. Barton, W. W. Tolbert, S. C. Myers, J. E. Vancil, H. A. Price, M. J. R. Vasko, E. E. Rutz, T. X. Wendeln and L. D. Rickertsen. 1980. Low-Level Waste Management: A Compilation of Models and Monitoring Techniques. ORNL/SUB-79/13617/2, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Murphy, E. S., and G. M. Holter. 1980. Technology, Safety, and Costs of Decommissioning a Reference Low-Level Waste Burial Ground. NUREG/CR-0570. Prepared for the U. S. Nuclear Regulatory Commission by Pacific Northwest Laboratory, Richland, Washington.

Napier, B. A., W. E. Kennedy, Jr., J. K. Soldat. 1980a. PABLM -- A Computer Program to Calculate Accumulated Radiation Doses from Radionuclides in the Environment. PNL-3209, Pacific Northwest Laboratory, Richland, Washington.

Napier, B. A., R. L. Roswell, W. E. Kennedy, Jr., D. L. Strenge. 1980b. ARRRG and FOOD -- Computer Programs for Calculating Radiation Dose to Man from Radionuclides in the Environment. PNL-3209, Pacific Northwest Laboratory, Richland, Washington.

Owen, P. T., N. S. Dailey, C. A. Johnson and F. M. Martin. 1979. *An Inventory of Environmental Impact Models Related to Energy Technologies*. ORNL/EIS-147, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Pleasant, J. C. 1979. *INGDOS -- A Conversational Computer Code to Implement U. S. Nuclear Regulatory Commission Regulatory Guide 1.109 Models for Estimation of Annual Doses from Ingestion of Atmospherically Released Radionuclides in Foods*. ORNL-TM-6571, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Pleasant, J. C., L. M. McDowell-Boyer and G. G. Killough. 1980. *RAGTIME: A FORTRAN IV Implementation of a Time Dependent Model for Radionuclides in Agricultural Systems, First Progress Report*. NUREG/CR-1196, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Rider, J. L. 1979. *AIRWAY -- A Fortran Computer Program to Estimate Radiation Dose Commitments to Man from the Atmospheric Release of Radionuclides*. WAPD-TM-12775, Bettis Atomic Power Laboratory, West Mifflin, Pennsylvania.

Rogers, V. C. 1979. *A Radioactive Waste Disposal Classification System*. NUREG/CR-1005, Prepared for the U. S. Nuclear Regulatory Commission by Ford, Bacon and Davis Utah, Inc., Salt Lake City, Utah.

Science Applications, Inc. 1979. *Tabulation of Waste Isolation Computer Models, Volume 1*. ONWI-78, SAI/OR-749-2. Prepared for Battelle Memorial Institute, Office of Nuclear Waste Isolation (ONWI), Columbus, Ohio.

Shaeffer, D. L. and E. L. Etnier. 1979. *AQUAMAN -- A Computer Code for Calculating Dose Commitment to Man from Aqueous Releases of Radionuclides*. ORNL/TM-6118, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Soldat, J. K., N. M. Robinson, D. A. Baker. 1974. *Models and Computer Codes for Evaluating Environmental Radiation Doses*. BNWL-1754, Pacific Northwest Laboratory, Richland, Washington.

Strenge, D. L., E. C. Watson, J. G. Droppo. 1976. *Review of Calculational Models and Computer Codes for Environmental Dose Assessment of Radioactive Releases*. BNWL-B-454, Pacific Northwest Laboratory, Richland, Washington.

Strenge, D. L., T. J. Bander. 1981. *MILDOS -- A Computer Program for Calculating Environmental Radiation Doses from Uranium Recovery Operations*. NUREG/CR-2011, PNL-3767, Pacific Northwest Laboratory, Richland, Washington.

U. S. Nuclear Regulatory Commission. 1981. *Draft Environmental Impact Statement on 10CFR61 "Licensing Requirements for Land Disposal of Radioactive Waste."* NUREG-0782, Office of Nuclear Materials Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D. C.

Watts, J. R. 1976. Modeling of Radiation Doses from Chronic Aqueous Releases. DF-MS-75-126, Savannah River Laboratory, Aiken, South Carolina.

3.0 INDIRECT BIOTIC TRANSPORT IN TERRESTRIAL SYSTEMS

Biota may be involved in radionuclide transport of buried low-level waste through transport enhancement, intrusion/active transport, or secondary transport.

3.1 TRANSPORT ENHANCEMENT

Biota can enhance the probability of 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.

Burrowing activity of mammals and invertebrates in the soil cover directly over waste results in a series of tunnels and chambers. For waste products that generate gases (e.g. physical decay of Ra-226 to Rn-222 or decomposition of organic components), these channels may help promote gas escape to the atmosphere. T. E. Hakonson estimated that up to two miles of pocket gopher tunnels over a low-level waste burial site at Los Alamos National Laboratory. Vogel et al. (1973) reports that prairie dogs constructed their mounds in such a manner as to promote wind-induced ventilation through their tunnels. Thus, any gaseous decomposition products accumulating in below-ground channels would be effectively vented to the surface. Tunnel systems created by small mammals, ants and decomposing plant roots may also enhance the passage of surface water through waste burial ground covers. Contaminants may then be solubilized and transported by soil water.

Burrowing mammals may bring about the eventual transport of buried waste through activities which result in increased erosion (Winsor and Whicker 1980). For example, pocket gophers, by depositing freshly disturbed soil on the surface in the process of tunnel digging, may accelerate the removal of the soil covering buried waste. After a few years or more, the cover may be reduced to the extent that the waste is more available for transport by physical and biological vectors.

Waste could enter decomposer food webs where buried materials include decomposable organic matter (e.g. lab coats, paper products, wooden containers, agar, plant and animal tissues, etc.). Mammals may affect larger items by shredding and chewing to initiate and accelerate the decomposition process. Such activity has been observed in the solid waste disposal area at Idaho National Engineering Laboratory. where small mammals burrowed into buried waste and used portions of the waste materials to construct nests. Decomposers, including many soil invertebrates such as earthworms and insect larvae, further reduce the organic fragments by passing them through their digestive system. Reichle et al. (1971) demonstrate that earthworms in the soil at Oak Ridge National Laboratory significantly influence the breakdown rate of soil organics, enhancing the availability of Cs-137 to plants. Witkamp (1972) also shows that the actions of decomposers such as snails and millipedes increase the leachability of Cs-137 and thus permit an increased uptake by plants. Fungi and other microorganisms continue the decomposition process. Mycorrhiza (a symbiotic association of specific soil fungi and root hairs) have been shown to increase the availability of Cs-137 to plant roots (Gamble 1971). Many products of decomposition include gases such as methane, carbon dioxide, and hydrogen sulfide (Odum 1971), which can diffuse through soil covers or flow in cracks, tunnels and channels to the surface.

The process of decomposition can also have an impact on the mobility of elemental radionuclides at waste sites. Wildung and Garland (1977), in a study of effects microorganisms have on the solubility of Pu in the soil, suggest that solubility might be influenced indirectly by microbe-produced organic compounds which form stable, soluble complexes. Many organics form complexes with mineral elements (nutrients and their analogs) that enhance uptake by plants. One method by which this occurs is chelation. A complex with metal ions is formed; the compound remains in solution and nontoxic (Odum 1971). Radionuclides subject to chelation will be more available for uptake by plants.

3.2 INTRUSION/ACTIVE TRANSPORT

Intrusion/active transport is the process most commonly considered for biotic transport of radionuclides from buried waste. Plant roots penetrate the waste zone; the radioactive material is then translocated through roots and stems to the aboveground portion of the plants (Rickard and Klepper, 1976). A horizontal belowground distribution of contaminants may occur through action of the root system as well. This process, responsible for "loss of containment," allows other cycling processes to take over.

3.2.1 Plants as Vectors

Fitzner et al. (1979) report 300 pCi/g Cs-137 in snowy buckwheat (*Eriogonum niveum*) on a burial ground at the Hanford site. They suggest that the relatively high concentration in plant tissue indicates plant root penetration into the buried waste. Klepper et al. (1979) report that rabbitbrush plants (*Chrysothamnus nauseous*) growing over a liquid waste disposal crib (i.e. effectively buried) contained amounts of radionuclides readily detectable with survey instruments. Excavation of these plants showed that Cs-137 was distributed in the leaves as well as in the taproot and lateral roots. Klepper further reported that Cs-137 concentrations in those leaves ranged up to 891 nCi/g. The plants also contained detectable quantities of Ce-144, Ru-106, Zr-95 and Mn-54. Although the age of the plants is not reported, the shrubs were certainly no older than 17 years, since that was the elapsed time since construction of the crib. The maximum depth to which contaminated roots were excavated was approximately 2-1/4 meters.

Paine et al. (1979) report finding Cs-137 in vegetation growing on a Hanford waste pond site decommissioned in 1954. Soil erosion occurred between 1954 and 1972 and Russian thistle (*Salsola kali*) plants growing on the site became contaminated. (*Agropyron sibericum*) and cereal rye (*Secale cereale*) were planted in an effort to stabilize the soil over the buried sediments. Six years later, Cs-137 was detected in the Siberian wheatgrass. The study showed that 0.002 percent of the total calculated site radionuclide inventory was incorporated by the wheatgrass. The authors attribute the accumulation of Cs-137 in the vegetation to a combination of factors, including too little backfill originally placed over the contaminated sediments and soil erosion, which reduced the thickness of soil cover.

Arthur (1982) finds significantly greater concentrations of transuranic radionuclides (Pu-238, Pu-239, Pu-240 and Am-241) in vegetation growing at Idaho National Engineering Laboratory on a solid radioactive waste disposal (burial) area than in similar vegetation from a control site. His studies led him to the conclusion that uptake from subsurface soils at the burial site was the predominant source of elevated radionuclide concentrations.

Dabrowski (1973) reports that Russian thistle plants containing elevated levels of radionuclides were observed in three separate burial grounds on the Hanford site in 1973. Previous annual surveys had not detected radioactive materials in Russian thistles in these areas. Readings of up to 10,000 cpm were obtained using a survey instrument. Samples taken of the contaminated plants revealed that radionuclides present included Cs-137, Zn-65 and Co-60. Concentrations of the unreported radionuclides for component parts of one plant were: root, 11 nCi/g; stem, 46 nCi/g; and leaves, 60 nCi/g.

Cornam (1979) reports on the operating experience at a Savannah River burial ground. In his report, he states that "...uptake by vegetation is one of the most common routes for dispersal of radioactivity." Ten incidents of vegetation contamination were observed between 1965 and 1975. The radioactivity levels in the vegetation were of the order of a microcurie per gram of vegetation or less. Cornam indicates that deep-rooted plants were able to reach through the soil cover and penetrate the radioactive waste.

Webster (1979) mentions the role of vegetation in returning radionuclides to the human environment in his report on land burial of solid radioactive waste at Oak Ridge National Laboratory. He comments that very little study has been done, but that an unpublished report in 1964 showed that grasses on the surface of the burial ground had assimilated unidentified radionuclides in their tissues.

These examples of radionuclide uptake by plants growing over radioactive waste burial sites are not comprehensive, but they do indicate that a variety of radionuclides, including fission products, activation products and transuranics, have been assimilated by plants and transported aboveground. Uptake occurs in both semiarid and moist habitats; plants documented include grasses, forbs, and shrubs. Trees no doubt would behave similarly, given time to become established over waste burial sites. In general, deep-rooted vegetation appears most likely to contact waste and become involved in radionuclide transport. Waste burial site managers commonly remove contaminated vegetation from the surface of the burial ground and rebury it. Certainly the potential for radionuclide transport by plants will increase after management at existing burial sites ceases.

3.2.2 Small Mammals as Vectors

Burrowing animals may also penetrate soil covers of low-level waste burial sites and mobilize contaminants. Paine et al. (1979) report that pocket mice had apparently excavated contaminated soil and moved it to the surface at a former waste pond site where sediments had been buried. They report mean Cs-137 concentrations in surface soil of 17 pCi/g. The mean value for samples from mouse burrows was 268 pCi/g.

A study on burrowing depth and soil displacement by the Great Basin pocket mouse (Perognathus parvus) was prompted by the abundance of those burrowing mammals on the Hanford site, where a number of waste burial areas exist (Landeen and Mitchell 1981). Those researchers conducted the study to provide a quantitative estimate of how deep the mice burrow and how much soil had been brought to the surface by the burrowing mammals and then to recommend possible mitigation measures to limit burrowing activity. They indicate that the volume of individual pocket mouse burrows ranged up to 11,000 cm^3 and are as deep as 1.4 m. They conclude that the pocket mice burrow deeper on disturbed sites (i.e. waste burial grounds) where backfill has not been properly compacted. According to J. Arthur at the Idaho National Engineering Laboratory (INEL), small mammals have burrowed into buried waste at INEL. Tissue samples and thermoluminescent dosimeter measurements confirm animal contact with the waste. Fitzner et al. (1979) also confirm small mammal contact with buried wastes at Hanford using the same techniques.

Winsor and Whicker (1980) report data showing that pocket gophers (Thomomys talpoides) effect the vertical as well as horizontal redistribution of plutonium in soil. For the Rocky Flats site they estimate that the monthly average quantity of soil moved to the surface was 155 kg/ha for the period March-October. They estimate that 0.5% of the soil plutonium inventory may be cast to the surface by pocket gophers during a decade.

O'Farrell and Gilbert (1975) report on the direct intrusion by a larger mammalian species (probably a badger or coyote) burrowing into a waste crib on the Hanford site. Fitzner et al. (1979) identify several mammals on the Hanford site (badgers, ground squirrels and pocket mice) with potential for burrowing into buried waste.

We have personally observed colonization of a uranium mill tailings pile in Grand Junction, Colorado by prairie dogs. The animals burrowed through the relatively thin soil covering and then mounded tailings at the entrance of their burrows.

Mammals that burrow into buried waste may transport contaminants by three means: 1) they may physically displace contaminated items or soil by digging and nestbuilding activity; 2) while in proximity with the waste, they may become externally contaminated and redistribute potentially hazardous material in their day-to-day movements; and 3) finally, the animals may ingest contaminants and spread the material by their feces or carcasses when they die.

3.2.3 Invertebrates as Vectors

Invertebrates comprise another major group of animals having a potential for moving buried wastes to the surface. Harvester ants (several species) inhabit most states west of the Mississippi River. Maximum tunneling depths of 2 or 3 meters for these ants have been reported widely. Because these ants exhibit a preference for disturbed areas, their occurrence on burial sites is very likely in some locales. Fitzner et al. (1979) report a total occurrence of 708 colonies on five burial grounds examined on the Hanford site. Using literature reports of volumes of soil moved by harvester ant colonies, these researchers estimate that those insects may transport 150 kg of soil to the surface per year. An analysis of soil samples from ant mounds at one location on the Hanford site where small mammals were observed to be excavating contaminated soil, though, revealed only background levels of radionuclides.

Earthworms are known for their ability to mix soils and may be relatively abundant at moist sites. They also develop well-defined burrow systems 3 to 6 ft deep (Smith 1974). Very little work has been done to evaluate radionuclide transport from burial sites by these invertebrates.

Their abundance, general habitat requirements and life style, however, clearly indicate potential for radionuclide transport.

3.3 SECONDARY TRANSPORT

Biota may mobilize radionuclides from low-level waste burial sites through secondary transport. Here the 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. According to W. H. Rickard, an experienced Hanford ecologist, the flow of subsurface water percolating through buried waste at Maxey Flats, a waste burial site in Kentucky, is a potential source of contaminants for plants outside the burial ground boundary.

Secondary transport may also involve the physical transport of contaminated materials. Consider, for example, a burial ground in the semiarid western states. Subsequent to covering of buried waste, the disturbed soil surface may be invaded by Russian thistle. This annual forb, characteristic of disturbed sites, has a deep root system and contamination on waste sites has been frequently documented (Panesko et al. 1980). In the fall, the mature plant dries, detaches at the soil surface and is blown by the wind until it encounters some obstruction (fences, ditches, water bodies). Russian thistle and similar plants have the potential for bringing about an initial vertical movement followed by a secondary, wind-assisted horizontal redistribution of contaminants.

The coupling of physical and biological transport by biogeochemical cycling processes is well known. One of the better documented examples for a waste burial situation occurred at the Hanford site. O'Farrell and Gilbert (1975) report the occurrence of contaminated fecal pellets of black-tailed hares (Lepus californicus) that were distributed over a 10 km^2 area in the vicinity of a waste disposal crib. Apparently the initial access to the waste resulted from animal burrowing, probably by badgers or coyotes; the waste form, which was described as a salt cake, was sought by the hares. The spread of contamination by the animals was probably initiated sometime between 1958 and 1960 and occurred until animal access to the site was sealed in 1964. No further study on the area was conducted until the mid 1970's. At that time, analysis of regurgitated pellets (castings) from raptors (birds of prey) using the area revealed low levels of contaminants, including Cs-137. These pellets consisted of nondigested remains of prey eaten by the birds, in this case hair and bones of small mammals. Although some other unknown source of Cs-137 available to the small mammals cannot be completely ruled out, it seems likely that the cesium being cycled was that originally dispersed by the hares. Transport pathways implied are either direct contamination of small mammals by cesium from decomposing fecal pellets, or by plant incorporation and subsequent ingestion leading to internal contaminants in the mammals. No raptors were sampled, but it is fairly evident they also obtained some degree of cesium contamination, although probably very small. Their daily feeding activity and seasonal migrations imply further means for transport and dispersal of radionuclides--presumably those initially buried in place in a backfilled trench.

3.4 GENERAL OBSERVATIONS CONCERNING TERRESTRIAL BIOTIC TRANSPORT FROM BURIED LOW-LEVEL RADIOACTIVE WASTE

Relatively little of our knowledge concerning biotic transport potential from shallow-buried waste is the result of thorough or systematic study. The examples of biotic transport provided here are largely the result of routine monitoring activity that has detected contaminants in the biota on or near waste burial sites. The usual response of waste management personnel to the discovery of biotic contamination has been to remedy the problem in the most expeditious manner. Plants found to be contaminated, for example, are routinely buried. Thus, data on the associated waste form, radionuclide concentrations, and intermediate transfer pathways are limited.

Existing evidence indicates that biota may either modify the immediate waste burial site environment to accelerate transport processes or act as transport vectors. Transport processes are a part of natural cyclic phenomena by which materials are moved from one ecosystem component to another. They occur in both moist and semiarid sites and involve all functional groups of organisms (producers, consumers and decomposers). Abiotic processes, such as erosion, percolation of surface water and leaching, are integrally associated with the potential for biotic mobilization of wastes. In general, wastes that have been more deeply buried in arid landscapes appear to be more effectively isolated from biotic transport, at least in the short run. Thus, biotic transport mechanisms appear to be a (usually) natural process whereby wastes are decomposed, mixed and dispersed in the environment. That dispersal process becomes much more rapid once the radionuclides reach the surface of the burial facility or after erosion has reduced the thickness of the overburden.

Elements having concentration ratios considerably less than one (plutonium for example) are discriminated against in trophic level transfer. Therefore lengthy biotic transport pathways where elements are passed through several producer/consumer/decomposer cycles have little potential for contributing a significant dose to man. The role of the biota in transfer of these elements from low-level waste burial facilities is more likely to involve physical displacement, reduction of soil covers or other mechanisms by which particulates are exposed to direct physical transport. Inhalation of the transported waste by man would appear to be the most probable final step resulting in exposure to man from biologically enhanced mobilization of wastes.

Elements which may be transferred freely through food webs (generally those having concentration ratios approaching one or greater) have the potential for a continual migration from burial sites by trophic level transfer and cycling processes. Scenario development should include the very long-term potential for accumulation of longer-lived radionuclides in the unconfined environment. Radionuclides such as I-129, Tc-99, and C-14 appear to have the greatest biotic transport potential. Strontium-90 and Cs-127 are examples of other radionuclides with a somewhat diminished opportunity to accumulate in the environment as a result of shorter radiological half-lives.

Management of burial sites, including activities such as removing and burying contaminated plants, applying herbicides to limit vegetative growth, mowing vegetative covers to limit establishment of deep-rooted plants, filling entry holes dug by mammals, and maintaining exclosure fences, have been effective in the short term in limiting radioactive material movements away from burial sites. However, such maintenance activities do not reduce the long-term potential for biotic transport. In fact, after LOIC occurs, biotic transport could increase substantially at existing burial facilities.

Existing evidence points to a diversity of biotic transport routes and mechanisms for toxic material movement from low-level waste burial sites.

On a day to day basis and given proper management, transport may indeed be controlled to a negligible level. It does not seem justifiable, however, to assume that the long-term impact of biotic transport will pose no significant impact and is therefore unworthy of detailed evaluation.

3.5. REFERENCES

Arthur, W. J. 1982. Radionuclide concentrations in vegetation at a solid radioactive waste disposal area in Southeastern Idaho. J. Environ. Qual. In press.

Cornam, W. R. 1979. Improvement in operating incident experience at the Savannah River burial ground. Pp. 787-794. In: Carter, M. W., A. A. Moghissi and B. Kahn (eds.), Management of Low-Level Radioactive Waste Volume 2. Pergamon Press, Elmsford, New York.

Dabrowski, T. E. 1973. Radioactive Tumbleweed in the 100 Areas. UNI-65, United Nuclear Industries, Inc., Richland, Washington.

Fitzner, R. E., K. A. Gano, W. H. Rickard and L. E. Rogers. 1979. Characterization of the Hanford 300 Area Burial Grounds. Task IV - Biological Transport. PNL-2774, Pacific Northwest Laboratory, Richland, Washington.

Gamble, J. F. 1971. Proposed mechanism for the recycling of radiocesium in Florida soil-plant systems. In: Radionuclides in Ecosystems, 3rd National Symposium on Radioecology. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Hakonson, T. E. and K. V. Bostick. 1976. The availability of environmental radioactivity to honey bee colonies at Los Alamos. J. Environ. Qual. 5(3): 307-310.

Klepper, E. L., L. E. Rogers, J. D. Hedlund and R. G. Schreckhise. 1979. Radioactivity Associated with Biota and Soils of the 216-A-24 Crib. PNL-1948. Pacific Northwest Laboratory, Richland, Washington.

Landeen, D. S., and R. M. Mitchell. 1981. Intrusion of Radioactive Waste Burial Sites by the Great Basin Pocket Mouse (Perognathus parvus). RHO-SA-211. Rockwell Hanford Operations, Richland, Washington.

Odum, E. P. 1971. Fundamentals of Ecology. Third ed. W. B. Saunders Company, Philadelphia, Pennsylvania.

O'Farrell, T. P. and R. O. Gilbert. 1975. Transport of radioactive materials by jackrabbits on the Hanford Reservation. Health Phys. 29: 9-15.

Paine, D., K. R. Price and R. M. Mitchell. 1979. Evaluation of a Decommissioned Radwaste Pond. RHO-SA-99, Rockwell Hanford Operations, Richland, Washington.

Panesko, J. V., D. E. Bihl, G. F. Boothe, R. L. Dirkes, K. Kover and R. E. Wheeler. 1980. *Environmental Protection Annual Report -- CY 1978*. RHO-LO-79-75, Rockwell Hanford Operations, Richland, Washington.

Reichle, D. E., D. A. Crossley, C. A. Edwards, J. F. McBrayer and P. Sollins. 1971. Organic matter and ^{137}Cs turnover in forest soil by earthworm populations: application of bioenergetic models to radionuclide transport. CONF-710501-PL, Third National Symposium on Radioecology, Oak Ridge, Tennessee.

Rickard, W. H. and E. L. Klepper. 1976. *Ecological Aspects of Decommissioning and Decontamination of Facilities on the Hanford Reservation*. BNWL-2033. Pacific Northwest Laboratory, Richland, Washington.

Smith, R. L. 1974. *Ecology and Field Biology*. Second ed. Harper and Row, New York.

Vogel, S., C. P. Ellington, Jr., and D. L. Kilgore, Jr. 1973. Wind induced ventilation of the burrow of the prairie dog, *Cynomys ludovicianus*. *J. Comp. Physiol*. 85: 1-14.

Webster, D. A. 1979. Land burial of solid radioactive waste at Oak Ridge National Laboratory, Tennessee: a case history. Pp. 731-746. In: Carter, M. W., A. A. Moghissi and G. Kahn (eds.), *Management of Low-Level Radioactive Waste Volume 2*. Pergamon Press, Elmsford, New York.

Wildung, R. E., and T. R. Garland. 1977. *The Relationship of Microbial Processes to the Fate and Behavior of Transuranic Elements in Soils Plants and Animals*. PNL-2416, Pacific Northwest Laboratory, Richland, Washington.

Winsor, T. F. and F. W. Whicker. 1980. Pocket gophers and redistribution of plutonium in soil. *Health Phys*. 39:257-262.

Witkamp, H. 1972. Transfer of 137-Cs from detritus to primary producer. Pp. 341-348. In: *Proceedings of Isotopes and Radiation in Soil-Plant Relationships Including Forestry*. December 13-17, 1972. IAEA, Vienna.

4.0 BIOTIC TRANSPORT IN AQUATIC SYSTEMS

Radionuclides from low-level waste (LLW) 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 LOIC; once the site is breached, transport to aquatic sites would be fairly rapid. Movement to surface waters via ground water would be relatively slow, and concentrations low due to radioactive decay and selective adsorption to soil particles.

Indirect routes are also feasible. For instance, weeds growing on or near buried wastes could assimilate radionuclides through their roots with subsequent transport to aboveground parts. Following death and abcission, the contaminated plant could be transported by wind into a lake or stream, where decay of the plant would contribute radionuclides to the aquatic system along with organic detritus. These radionuclides could then enter normal food web paths and eventually reach people. Wind erosion could blow contaminated particulate matter from LLW burial sites into lakes or streams; this matter could enter aquatic food webs, depending upon particle size and chemical form.

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 LLW burial sites. This section presents information relative (though not explicit) to biotic transport from aquatic sources.

4.1 TRANSPORT FROM AQUATIC SOURCES

Once radionuclides reach a surface water body, they could be incorporated into aquatic food webs; amounts would depend on such factors as the nuclide, its chemical form, and the complexity of the food web. Trivalent Cr-51, for example, occurs in the dissolved state; it is more likely to undergo transport than hexavalent Cr-51, which occurs as a particulate. Chemical constituents in receiving waters affect how radionuclides are taken up in the food web as well (Cushing 1970).

Once incorporated into the food web, radionuclides could enter the human food web. Contaminated food used by man would include waterfowl, fish, upland game birds, and mammals that feed on contaminated biota or drink contaminated water. Radionuclides entering streams from LLW burial sites enter food webs similar to those in lakes, but they have the potential of impacting a greater area due to the physical transport of the water downstream.

4.2 POTENTIAL FOR BIOTIC TRANSPORT

Documented cases of biotic transport by aquatic biota from LLW burial sites are non-existent. Cases of organisms transporting radionuclides from contaminated aquatic environments have been documented, however, and there is no reason to believe that the same could not occur on LLW sites.

Nelson (1964) estimates that midge larvae emerging from the contaminated sediments of the Clinch River removed 3.55×10^{-5} Ci Sr-90$\cdot m^{-2} \cdot yr^{-1}$ from the river bottom. He further calculates that fallout Sr-90 adds 45 times as much Sr-90 to the river as is removed by the emerging insects, thus indicating that these insects are of no great importance in the overall dispersion of Sr-90. Davis (1958) reports that caddisflies (Hydropsyche cockerelli) emerging from the Columbia River near

Hanford average 3×10^{-4} Ci/g wet weight of total beta activity, and that midges (subfamily Orthocladiinae) average 2×10^{-2} Ci/g wet weight.

Both wasps and swallows have been observed building their nests against buildings with radioactive mud on the Hanford site (Panesko et al. 1980). Similar occurrences might result if sediments were rendered radioactive by contaminated surface waters from LLW sites.

Another documented incident which could be related to LLW burial sites is the uptake of radionuclides by waterfowl from Gable Mountain Pond, a water body which receives low-level radioactive liquid wastes. Cushing and Watson (1974) restricted wild ducks to the pond and compared accumulated 137-Cs concentrations in the flesh with those of unrestricted wild ducks and resident coots. The restricted ducks, forced to feed on contaminated food, accumulated an average of 320 pCi/g dry weight as compared to 60 pCi/g dry weight for unrestricted ducks; the latter fed mainly away from the pond. The coots contained an average of 570 pCi/g dry weight.

4.3 INFORMATION NEEDED TO COMPLETE AQUATIC SCENARIOS

Perhaps the most significant information concerning the movement of radionuclides from LLW burial sites are meaningful data on actual amounts and rates of movement to aquatic sites. Scenarios were presented in the first portion of this section which described possible ways for radionuclides to reach aquatic sites. Transport subsequent to the entrance of radionuclides into lakes or streams is discussed below.

After radionuclides reach lakes or streams, they cycle within aquatic food webs. To understand these food webs completely, we need to know about the major components: (1) decomposers, (2) producers, and (3) consumers. Our concern is whether food eaten by man could attain a level which is important relative to doses received from pathways normally considered in impact assessment. Cycling within these food webs will be no different, except perhaps in terms of concentration, than what we currently know of transport of these radionuclides. Therefore, gaps in our knowledge can be applicable to our present concern. Knowledge based on literature with food-web cycling in aquatic systems is fairly complete, at least in terms of transfer among major components of the ecosystem. Sufficient knowledge already exists to describe the process of radionuclide transfer in aquatic systems.

In summary, the likelihood of significant amounts of radionuclides reaching aquatic surface sites is remote, at least under present waste burial conditions. Even if radionuclides do reach surface waters, they will be cycled in aquatic food webs in the same way as those discharged via other methods and be considered no differently in models predicting dose presently in use. In other words, unique routes from LLW burial sites to water may be found, but once in surface waters, their cycling will not follow unique pathways.

4.4 REFERENCES

Cushing, C. E. 1970. Radiation ecology in freshwater communities. Pp. 45-56. In: Man and Aquatic Communities. Oregon State University Water Resources Research Institute, Oregon State University, Corvallis, Oregon.

Cushing, C. E. and D. G. Watson. 1974. Aquatic Studies of Gable Mountain Pond. BNWL-1884, Pacific Northwest Laboratory, Richland, Washington.

Davis, J. J. 1958. Dispersion of radioactive materials by streams. J. Amer. Water Works Assoc. 50:1505-1515.

Nelson, D. J. 1964. Biological vectors and reservoirs of strontium-90. Nature 203:420.

Panesko, J. V., D. E. Bihl, F. G. Boothe, R. L. Dirkes, K. Kover and R. E. Wheeler. 1980. Environmental Protection Annual Report - CY 1978. RHO-LO-79-75, Rockwell Hanford Operations, Richland, Washington.

5.0 A SCREENING OF RADIONUCLIDES FOR BIOTIC TRANSPORT POTENTIAL TO MAN

Many classification schemes exist for assessing the hazard of radionuclides to man (see review by Smith et al. 1980). These classification schemes generally are based upon the hazard index (HI). The hazard index is defined as the amount of the radionuclide present (curies) divided by the maximum permissible concentration of that radionuclide in water or air (curies per cubic meter). The latter figure is taken from the Code of Federal Regulations. The hazard index measures toxicity and refers to the quantity of air or water required to dilute a given quantity of radionuclide to its maximum permissible concentration. Many indices expand upon the hazard index by including information pertaining to one or more of the following factors: transport in the soil or other media, half-life, intake rates, and decay products. Only a few indices consider biological pathways and these are strictly agricultural food pathways (Adam and Rogers 1978; Smith et al. 1980). To make an assessment of biotic transport, some of the above properties were considered in addition to characteristics relating to the biota and the relative quantity of radioactive material in low-level waste.

A decision analysis procedure of two steps was used to screen the radionuclides. The first step involved developing a list of criteria which would identify those elements susceptible to biotic transport. Associated with each criterion was a scaling factor, e.g., the half-life criterion was given a scale of from a few to hundreds of years. Scales chosen were related to biotic transport. The second step involved evaluating the radionuclides relative to the criteria. Radionuclides were evaluated by a group of scientists representing the disciplines of terrestrial and aquatic ecology, dose assessment modeling, and environmental chemistry.

More sophisticated quantitative ranking systems do exist (Smith et al. 1980). However, even these methods utilize subjective judgements to assign missing parameter values. Given the lack of information on biotic transport and of models from which to obtain parameter values, the decision analysis procedure was an easily utilized alternative.

5.1 RADIONUCLIDE RANKING CRITERIA

Six criteria were considered to be sufficiently important to biotic transport to be included in the screening process. These were:

Waste Inventory. This criterion refers to the amount and/or activity of the radionuclide disposed of in low-level waste management sites; it is the quantity factor of the hazard index. In the context of biotic transport, presumably the greater the amount disposed of, the greater the potential for biotic transport. The scale for this criterion is the radioactivity of the waste material (low to high).

Half-Life. This criterion refers to the length of time the environment will be exposed to the radionuclide. For low-level waste the radionuclide has either gone through a prior "use" stage, as for example research and medical waste, or was a contaminant in the nuclear fuel cycle. This "use" plus the time required for shipping and disposal operations, means that materials of very short half-lives (on the order of days) are no longer present and are thus not available for biotic transport. Examples of biotic transport given in previous sections of the report commonly included Cs-137, Sr-90 and Co-60, elements with half-lives of several years. Many radionuclides with very long half-lives (actinide elements, I-129 and Tc-99) were infrequently detected in connection with biotic transport from low-level waste. Though the reasons for this are unclear at this point, the relative difficulty in locating these radionuclides by survey methods is probably a contributing factor. Moreover, these radionuclides are usually found at lower concentrations in low-level buried waste. The longer lived (hundreds of years and greater) radionuclides however may have the greatest potential for biotic transport and subsequent dose to man because of the length of time available for transport and potentially greater transport rates after LOIC. The scale is years (a few years to centuries or longer).

Concentration Ratios. Concentration ratios were used as familiar and general indices of the bioavailability of radionuclides. Although concentration ratios apply strictly to plants (concentration in plant material/concentration in soil), materials that are available to plants are generally available to animals. Thus concentration ratios relate more to intrusion pathways than to the physical movement of radionuclides by the biota. Cesium-137 for example, with an easily detected energy and relatively high concentration ratio, was among the most frequently observed radionuclides in plant tissue (see section on indirect transport in terrestrial systems). The scale ranges from low to high concentration ratios.

Pathway to Man. This criterion refers to the potential for transfer through the food web to man. The uptake of radionuclides by the biota may follow several pathways (see Section 3), each with a different probability of occurring and of ultimately transferring the radionuclide to man. Some elements may be more susceptible to transport through transport enhancement and/or intrusion/active transport. The scale ranges from highly improbable and indirect to direct.

Geographical Area Potentially Affected. This criterion refers to the geographical area that could potentially be affected by biotic transport. Included in the definition is an assessment of the mobility of the radionuclide once incorporated into a biotic pathway. For example, an element may be readily absorbed by an animal, but stored in bone where the potential for further transfer is small. The scale for this criterion is the proportion of land or water area affected (small to large).

Immediacy of Potential Impact. This criterion refers to the potential timing of any impact from the disposal and subsequent transport of

TABLE 5.1. Criteria and Weights for Screening Radionuclides on Their Potential for Biotic Transport

Weight	Criteria
29	Geographical area potentially affected (small to large proportion)
17	Pathway to man (indirect improbable to direct)
15	Immediacy of impact (hundreds of years to less than a year)
14	Concentration ratios (low to high concentration ratios)
13	Waste inventory (units of mass or radioactivity)
12	Half-life (seconds to years)

a radionuclide. This criterion is highly dependent on waste form. The role of waste form (both chemical and physical) ranges from that of facilitating to discouraging active transport. The example at Hanford, in which black-tailed hares were attracted to exposed radioactive salt cakes, indicates how waste form may enhance transport potential. One can envision an opposite relationship between waste form and biotic transport for massive solid waste such as activated reactor components. Thus, waste form would resist physical displacement and degradation by burrowing animals and would effectively contain the radionuclides, thereby making them unavailable for ingestion or uptake by plants. The scale ranges from hundreds of years to less than a year.

To weight the criteria, pairs of criteria were compared, and the participants asked to chose which was most important. All possible random pairs were evaluated by each participant; the preferences were then translated to numerical values. These values were entered into a matrix with a zero diagonal. Row totals were divided by the grand total to give a proportional weight for each criterion, the sum of all weights being one. Criteria weights, converted to percentages, are listed in Table 5.1.

5.2 RADIONUCLIDE EVALUATIONS

The procedure for screening the radionuclides was to evaluate each element against the six criteria on a zero to five scale. Thus, for the half-life criterion, an element with a long half-life would be given a score of four or five while one with a relatively short half-life would be given a zero or one. If an evaluator felt the criterion was not applicable to a particular radionuclide, or that not enough information was available to evaluate that criterion, he could score a -1, which was then excluded from the final score. The -1 could also be used for any element the participant did not feel qualified to evaluate. The scores for each criterion were summed over the number of respondents and the average computed; the average was then weighted by the criteria weights. Individual criteria scores were summed to provide an overall score for each element.

The ranked radionuclides are listed in Table 5.2. The order of the radionuclides represents the potential for biotic transport. This list of elements was developed from an initial list of 44 radionuclides recorded in low-level waste (Murphy and Holter 1980). Because of physical limitations with the decision procedure (i.e., 44 radionuclides × 6 criteria = 264 decisions), the initial list was reduced to 24 elements (144 decisions). Criteria used in this initial screening were inventory and half-life; those elements having a short half-life and low inventory were excluded. To include as many elements as possible, all isotopes were grouped together. This produced some conflict for several elements. Iodine, for example, has two common isotopes; while both may be important in biotic transport, one has a much longer half-life than the other. This grouping process may have biased the final scores since more weight could have been given to those elements with many isotopes; conversely, important isotopes may have been overlooked in the evaluation of the total element.

TABLE 5.2. Ranking of Radionuclides from Decision Analysis Screening Process

Rank	Radionuclide
1	Hydrogen (H-3)
2	Carbon (C-14)
3	Iodine (I-125, I-129)
4	Cesium (Cs-137)
5	Strontium (Sr-90)
6	Radium (Ra-226)
7	Technetium (Tc-99)
8	Cobalt (Co-60)
9	Neptunium (Np-237)
10	Uranium (U-235, U-238)
11	Nickel (Ni-59, Ni-63)
12	Thorium (Th-230, Th-232)
13	Iron (Fe-55)
14	Manganese (Mn-54)
15	Zinc (Zn-65)
16	Americium (Am-241, Am-243)
17	Plutonium (Pu-238 through Pu-242)
18	Ruthenium (Ru-106)
19	Antimony (Sb-124, Sb-125)
20	Europium (Eu-152, Eu-154, Eu-155)
21	Niobium (Nb-94)
22	Chromium (Cr-51)
23	Zirconium (Zr-95)
24	Rubidium (Rb-86)

The screening process also pointed up the fact that several of the criteria needed to be defined more strictly. Thus the criteria relating to geographical area affected included in its definition information on half-life and concentration ratios. Moreover, as we went through the process, the need for other criteria became evident. A criterion that incorporates decay product effects is of special concern, for example, if elements resulting from decay have a greater potential for biotic transport.

Comparing the results of this evaluation with other classifications for low-level wastes, we find general agreement on the top 10 to 15 elements (Table 5.3) but less agreement on specific ranking. Differences in rank for the various elements are the result of the criteria used for evaluation. Our classification procedure was unique in that it did not include a toxicity criterion since this procedure was an attempt to select for biotic transport potential and not hazard. Other primary differences in the results of this procedure were the inclusion of H-3 and Co-60 and the exclusion of Am-241 and Pu-239. Tritium and Co-60 are probably excluded from the other classifications because of their relatively short half-lives. These classifications are based on an LOIC of 150 (Adam and Rogers 1978) and 300 (Smith et al. 1980) years, when these two elements would have disappeared from the waste. Plutonium and americium were probably ranked lower in our screening because their inventory at low-level waste sites tends to be small. This, considered with the long half-lives of these elements, translates into a lower score on the immediacy of impact criterion.

Those elements appearing in Table 5.3 represent elements with a significant potential for becoming a waste management problem. These elements possess both a direct hazard to man as well as a high potential

TABLE 5.3. Comparison of Radionuclide Rankings in Five Studies

Radionuclide	Biotic Transport (This Study[1])	Food Pathway (Adam and Rogers 1980[2])	Food Pathway (Cohen and Jow 1978[3])	Drinking Water (Cohen and Jow 1978[4])	Drinking Water (Smith et al. 1980[5])
^{3}H	X				
^{14}C	X	X	X		
^{60}Co	X				
^{90}Sr	X	X	X	X	X
^{99}Tc	X	X	X		
^{129}I	X	X	X		X
^{137}Cs	X	X		X	X
^{226}Ra	X		X	X	
^{235}U	X	X	X		
^{238}U	X	X	X		
^{237}Np	X	X			X
^{239}Pu		X	X	X	X
^{241}Am		X		X	X

---

[1] Top ten radionuclides from screening procedure (uranium was considered as a single element)

[2] Maximum allowable concentration (MAC) for food products coming from contaminated soil. Loss of Institutional Control (LOIC) = 150 years. Listed elements were present in the top 14 (not listed: Cs-135, Pu-240, Pu-242, Am-243). (Cutoff: MAC < 20)

[3] Classification based on number of expected cancer doses (CD) from ingestion of contaminated food. Listed elements were present in the top 13 (not listed: Cl-36, Bi-207, Th-232, U-233, Pu-238). (Cutoff: CD > .01)

[4] Same as 3 but based on cancer risk from drinking water with an LOIC of 200 years. Listed elements were present in top 7 (not listed: U-233, Pu-238). (Cutoff: CD > .01)

[5] Geotoxicity hazard index for chronic ingestion of drinking water. LOIC = 300 years. Listed elements were the only ones evaluated.

for biotic transport. This potential would result in a greater distribution of the element and increase the probability of exposure to man. While tritium and Co-60 represent a transport potential primarily in the near-term, their continued production and subsequent disposal poses longer-term management problems.

5.3. REFERENCES

Adam, J. A. and V. L. Rogers. 1978. A Classification System for Radioactive Waste Disposal -- What Waste Goes Where? NUREG-0456, FBDU-224-10. Office of Nuclear Material Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D. C.

Cohen, B. L. and H. M. Jow. 1978. A generic hazard evaluation of low-level waste burial grounds. Nuclear Technology 41:381-388.

Murphy, E. S., and G. M. Holter. 1980. Technology, Safety, and Costs of Decommissioning a Reference Low-Level Waste Burial Ground. NUREG/CR-0570. Prepared for the U. S. Nuclear Regulatory Commission by Pacific Northwest Laboratory, Richland, Washington.

Smith, D. F., J. J. Cohen and T. E. McKone. 1980. A Hazard Index for Underground Toxic Material. UCRL-52889, Lawrence Livermore Laboratory, University of California, Livermore, California.

6.0 SUMMARY AND RECOMMENDATIONS

Licensing decisions regarding low-level waste (LLW) management are, of necessity, influenced by the results of predictive modeling. Our review of recent LLW literature, contained in Section 2 of this report, reveals 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 human health impacts 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 consider 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, as discussed in Sections 3 and 4 of this report. 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 LLW 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 that are of concern.

An example of a typical pathway scenario currently considered is the crop root penetration scenario. This scenario is considered in several current impact assessments (U. S. NRC 1981; Little et al. 1981; Murphy and Holter 1980). In this scenario, surface erosion is assumed to occur over a period of time, typically about 500 years. At the end of this erosion period, farm crop roots are assumed to penetrate a clean (uncontaminated) trench cover and enter a homogeneously contaminated waste zone. Only a small fraction of the roots are assumed to enter the waste zone. The resulting food crops are then assumed to be ingested by an individual, and radiation doses from ingestion are calculated. The waste profile normally postulated for this scenario is graphically illustrated in Figure 6.1. Based on the preliminary findings included in this report, biotic transport over that 500 year period has the potential for producing a soil concentration profile similar to the one in Figure 6.2. This profile could be established by the accumulated intrusion and active transport by plants or animals over this long time period. Although the short-term effects of biotic transport may be small, its accumulated effects may be to enhance the amount of waste that the roots eventually contact. Additionally, radionuclides brought up near the surface may lead to other human exposure pathways (e.g. inhalation of resuspended surface contamination).

We recommend that a defensible, reproducible methodology be developed to quantify the long-term impacts of biotic transport mechanisms.

As a first step, order of magnitude relationships should be developed and applied to a specific scenario (such as the crop root penetration scenario). This step can begin by extending the current scenario to include the full range of plant and animal species occurring on or near the

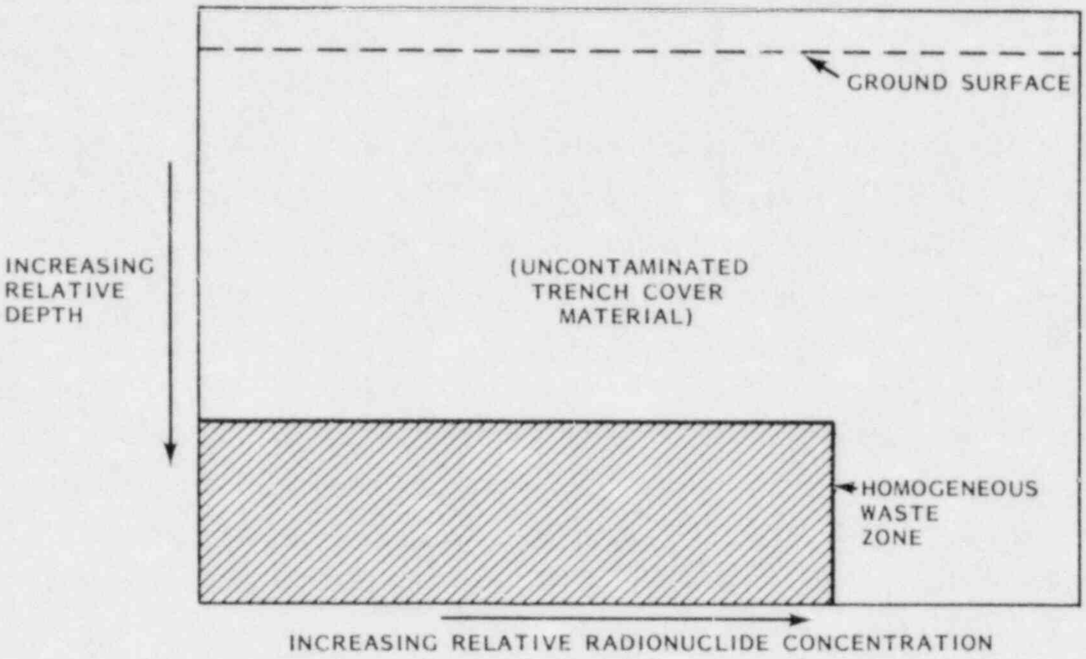

FIGURE 6.1. Waste Concentration Profile for a Typical Crop Root Penetration Scenario

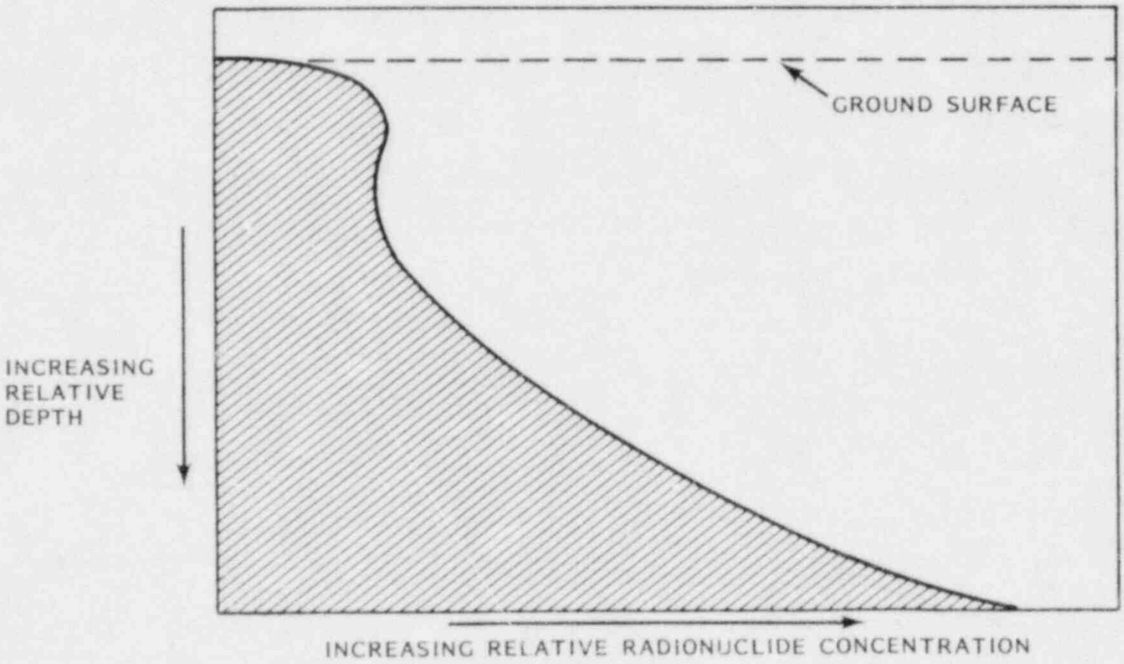

FIGURE 6.2. Potential Weste Concentration Profile Resulting from a Biotic Transport Scenario

waste site. The calculated results of the scenario with and without biotic transport should be compared, and model sensitivity to particular biotic mechanisms should be determined.

The second step would be to determine the elapsed time required for biotic mechansims and processes to become part of a plausible pathway for human exposure. Knowledge of this would permit the development of biotic transport scenarios which specifically address the times of critical importance.

The third step should be development of 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. It is recognized that 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 LLW disposal licensing implications of biotic transport processes.

At the conclusion of this effort, it will be possible to assess the potential significance of biotic transport of radionuclides from LLW sites based on modeling, field and ecological evidence. These results will provide the basis for an evaluation of the role of biotic transport in site selection and licensing decisions.

6.1 REFERENCES

Little, C. A., D. E. Fields, D. J. Emerson and G. Hiromoto. 1981. Environmental Assessment Model for Shallow-Land Disposal of Low-Level Radioactive Wastes: Interim Report. ORNL/TM-7943. Prepared for the U. S. Environmental Protection Agency by Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Murphy, E. S., and G. M. Holter. 1980. Technology, Safety, and Costs of Decommissioning a Reference Low-Level Waste Burial Ground. NUREG/CR-0570. Prepared for the U. S. Nuclear Regulatory Commission by Pacific Northwest Laboratory, Richland, Washington.

U. S. Nuclear Regulatory Commission. 1981. Draft Environmental Impact Statement on 10CFR61 "Licensing Requirements for Land Disposal of Radioactive Waste." NUREG-0782, Office of Nuclear Materials Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D. C.

ACKNOWLEDGEMENTS

This study was funded by the Nuclear Regulatory Commission. The authors wish to thank N. R. Hinds for editing the manuscript and G. L. Poole for typing.

DISTRIBUTION

No. of
Copies

OFFSITE

A. A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

179 U. S. Nuclear Regulatory Commission
Division of Technical Information and Document Control
7920 Norfolk Avenue
Bethesda, MD 20014

2 DOE Technical Information Center

5 John D. Randall
U. S. Nuclear Regulatory Commission
Mail Stop 1130 SS
Washington, DC 20555

J. J. Davis
U. S. Nuclear Regulatory Commission
Mail Stop 1130 SS
Washington, DC 20555

F. Swanberg
Health and Environmental Research Branch
Division of Safeguards, Fuel Cycle and Environmental Research
U. S. Nuclear Regulatory Commission
Washington, DC 20555

T. E. Hakonson
Group LS-6
M.S. K495
Los Alamos Scientific Laboratory
P. O. Box 16663
Los Alamos, NM 87545

No. of
Copies

OFFSITE

R. Harty
Center for Quantitative Science
University of Washington
3737 - 15th Ave. N. E.
Seattle, WA 98195

O. D. Markham
Radiological and Environmental Sciences Laboratory
U. S. Department of Energy
550 2nd Street
Idaho Falls, ID 83401

G. L. Swartzman
Center for Quantitative Science
University of Washington
3737 - 15th Ave. N. E.
Seattle, WA 98195

F. W. Whicker
Department of Radiology and Radiation Biology
Colorado State University
Fort Collins, CO 80523

ONSITE

45 Pacific Northwest Laboratory

K. E. Byers
L. L. Cadwell
J. F. Cline
C. E. Cushing
K. A. Gano
T. R. Garland
N. R. Hinds
E. A. Jenne
W. E. Kennedy, Jr.
D. F. Klopfer

DISTRIBUTION

No. of
Copies

ONSITE

Pacific Northwest Laboratory (cont.)

D. H. McKenzie (10)
B. A. Napier
I. C. Nelson
T. L. Page
R. W. Perkins
K. R. Price
W. H. Rickard
R. G. Schreckhise
L. C. Schwendiman
M. A. Simmons
J. K. Soldat
J. A. Strand
M. J. Sula
W. L. Templeton
J. M. Thomas
C. M. Unruh
B. E. Vaughan
W. L. Warner
E. C. Watson
Publishing Coordination (2)
Technical Information (5)

NRC FORM 335
(11 81)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-2675, Vol. 1
PNL-4241

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Relevance of Biotic Pathways to the Long-Term Regulation
of Nuclear Waste Disposal
A Report on Tasks 1 and 2 of Phase I

5. DATE REPORT COMPLETED

MONTH	YEAR
April	1982

7. AUTHOR(S) D. H. McKenzie, L. L. Cadwell, C. E. Cushing, Jr.
R. Harty, W. E. Kennedy, Jr., M. A. Simmons, J. K. Soldat,
G. Swartzman

DATE REPORT ISSUED

MONTH	YEAR
July	1982

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

Pacific Northwest Laboratory
P.O. Box 999
Richland, WA 99352

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*

Division of Health, Siting, and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.

11. FIN NO.
B2377

13. TYPE OF REPORT
Topical Technical Report

PERIOD COVERED *(Inclusive dates)*
5/81 - 3/82

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

The purpose of the work reported here was to evaluate the relevance of biotic transport to the assessment of impacts and licensing of low-level waste disposal sites. Available computer models and their recent applications at low-level waste disposal sites are considered. Biotic transport mechanisms and processes for both terrestrial and aquatic systems are presented with examples from existing waste disposal sites. Following a proposed system for ranking radionuclides by their potential for biotic transport, recommendations for completing Phase 1 research are presented. To evaluate the long-term importance of biotic transport at low-level waste sites, scenarios for biotic pathways and mechanisms need to be developed. Scenarios should begin with a description of the waste form and should include a description of biotic processes and mechanisms, approximations of the magnitude of materials transported, and a linkage to processes or mechanisms in existing models. Once these scenarios are in place, existing models could be used to evaluate impacts resulting from biotic transport and to assess the relevance to site selection and licensing of low-level waste disposal sites.

17. KEY WORDS AND DOCUMENT ANALYSIS
Models of Biotic Transport from Shallow
Land Burial of Low-Level Radioactive Waste

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*
Unclassified

20. SECURITY CLASS *(This page)*
Unclassified

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (11 81)

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FOURTH CLASS MAIL
POSTAGE & FEES PAID
USNRC
WASH. D. C.
PERMIT No. G 67

120555078877 1 ANRW
US NRC
ADM DIV OF TIDC
POLICY & PUBLICATIONS MGT BR
PDR NUREG COPY
LA 212
WASHINGTON DC 20555

OF NUCLEAR WASTE DISPOSAL