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Background Information for the Development of a Low-Level Waste Performance Assessment Methodology

Assessment of Relative Significance of Migration and Exposure Pathways

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Prepared for
U.S. Nuclear Regulatory Commission

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Background Information for the Development of a
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Volume 1 Identification of Potential Exposure Pathways
L. R. Shipers

Volume 2 Assessment of Relative Significance of Migration and Exposure Pathways
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Volume 3 Selection and Integration of Models
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Volume 4 Identification and Recommendation of Computer Codes
M. W. Kozak, M. S. Y. Chu, C. P. Harlan, and P. A. Mattingly

ABSTRACT

An assessment of the relative significance of pathways for the migration and exposure of radionuclides from a low-level waste disposal facility to man is described in this document. Initiating events and circumstances associated with the undisturbed, naturally disturbed, and artificially disturbed performance of low-level waste facilities are considered during the ranking procedure of potential migration and exposure pathways. In this ranking procedure, relative measures are assigned to the likelihood of occurrence of the events and circumstances leading to migration and exposure of radionuclides and to the potential level of significance in terms of dose to man. Based on this ranking procedure, a set of generic important pathways for low-level waste disposal facilities is developed and presented.

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PREFACE

The U. S. Nuclear Regulatory Commission (NRC) has the responsibility for licensing commercial disposal of low-level waste. NRC requires licensees to demonstrate compliance with the performance objectives in Sections 61.41 and 61.42 of Subpart C of 10 CFR Part 61 using performance assessments. A performance assessment is an evaluation of the potential impact to the general public from the operation of a low-level waste facility.

During the review and evaluation of license applications, NRC may need to perform independent evaluations of the low-level waste facility performance. Consequently, NRC needs to develop a method for confirming or verifying assertions and conclusions submitted by the applicant. A project was initiated by NRC to develop a performance assessment methodology for their use in the evaluation of license applications. The major phases of the project are (1) identifying initiating events and environmental pathways by which radionuclides can reach humans, (2) assessing the relative importance of the pathways identified in phase 1, (3) selecting and integrating models that are appropriate for a performance assessment analysis, (4) selecting a system of codes and techniques that support the selected models, and (5) assembling a full performance assessment methodology by implementing and integrating the codes and techniques selected in phase 4.

This publication documents the results of the first four phases of the project. These four volumes contain the background information used in the development and assembly of the full performance methodology. The information contained in these reports should be considered preliminary because many recommendations are based on literature review alone. As the methodology is implemented and integrated, the recommendations may change based on experience and insight gained from actual code performance.

1.0 INTRODUCTION

The objective of this document is to assess the relative significance of postclosure pathways of radionuclide release, migration, and exposure from near-surface low-level radioactive waste disposal facilities for a representative range of generic site conditions in terms of potential doses to the general population. The assessment of the relative significance of migration and exposure pathways supports development of a performance assessment methodology designed to assess compliance with the performance objectives in 10 CFR 61.41 and 61.42. The methodology is intended to be used by the Nuclear Regulatory Commission (NRC) staff for confirmatory analyses in support of license review activities for low-level waste disposal facilities. The pathways identified here as significant will be considered in conjunction with initiating events that result in the release of radionuclides from low-level waste disposal facilities to provide a basis for the definition of mathematical and conceptual models to be later identified for implementation in the methodology.

This document is an extension of previous work where most potential migration and exposure pathways from near-surface low-level waste disposal facilities were identified [Shipers, 1989]. A large number of potential migration and exposure pathways were identified in this previous work. It is important to ensure that all pathways with a high likelihood of resulting in a significant exposure to man are analyzed and their impacts evaluated because it is neither possible nor practical to analyze all of these potential migration and exposure pathways as a part of a performance assessment. It is undesirable to expend large amounts of the limited time and resources available for performance assessment in analyzing pathways that have a very low likelihood of resulting in significant doses to man. In this document the potential migration and exposure pathways will be ranked using generic criteria to identify which pathways may be most important in assessing compliance with the performance objectives in 10 CFR Parts 61.41 and 61.42. However, it is recognized that the level of significance of these identified important pathways will be determined from site specific information submitted by the applicant.

In order to assess compliance with 10 CFR Parts 61.41 and 61.42 it is necessary to determine the dose to the maximally exposed individual. This requires that exposures from different pathways and media be considered in parallel and the total doses determined. For example, in the case of contaminated ground water, human exposure may occur from both direct means (ingestion of, immersion in, and proximity to ground water) and indirect means (ingestion of contaminated plants and proximity to contaminated soils resulting from irrigation with contaminated ground water). The doses from these different migration and exposure pathways to an individual must be summed before they are compared to the performance objectives in 10 CFR Parts 61.41 and 61.42. The objective of this report is to identify sets of parallel pathways that may result in significant doses to man for various initiating events leading to the release of radionuclides from a disposal facility during the postclosure period.

While it is not a part of generic pathway identification and prioritization, a consideration of performance assessment in analyzing a specific site is the determination of the contribution of the source term to each of the parallel pathways that contribute to a final dose. Not only is it important to identify the source term, but those portions of the source term available for transport along each of the simultaneous pathways must be quantified. For example, the radioactive waste inventory that is leached through infiltration is not also available for suspension into the atmosphere during the same timeframe. In addition, the types of radionuclides that make up the source term may determine which of the potential pathways for analysis provide the most significant contribution to the final dose to man. The determination of the source term contribution to each of the parallel pathways and the manner in which the radionuclides in the inventory may determine which pathways provide the most conservative estimate of dose are site-specific issues. These issues should be addressed during site performance assessment and are not meant to be a part of the identification of pathways or determination of the significance of pathways in this generic analysis.

Initiating events and circumstances associated with the undisturbed, naturally disturbed, and artificially disturbed performance of near-surface low-level waste disposal facilities are considered during the ranking procedure of potential migration and exposure pathways. The actions of inadvertent intruders into a disposal facility are also considered in evaluating the relative significance of pathways. The pathways identified as significant in this document are appropriate for consideration in performance assessment of facilities utilizing the disposal options of shallow land burial, below-ground vaults, and earth-mounded concrete bunkers during the postclosure period. It should be noted that the phrase "disposal unit" as used in the remainder of this document is meant to represent a shallow land burial trench with its cap and/or the concrete structure utilized in the below-ground vault and earth-mounded concrete bunker disposal options.

A formal risk analysis was not performed as a part of the pathway assessment since the objective of the performance assessment is to demonstrate compliance of the established radiation standards and performance objectives as defined in 10 CFR 61. Values of risk, as calculated by the product of probability and consequence, were not determined for the various migration and exposure pathways. Numerical values of event probability were not calculated or assigned. Instead, a relative measure (low, high) of the likelihood of occurrence of the events and circumstances leading to migration and exposure of radionuclides along the pathway was assigned. No calculations of magnitude of consequences of radionuclide migration along pathways were performed. Again, a relative measure (low, high) of the potential level of significance in terms of dose to man was assigned. The identification of important pathways is based upon existing assessments [NRC, 1981abc;

McKenzie et al., 1982, 1983, 1984; Helton and Kaestner, 1981; Soldat et al., 1974], simple calculations and expert judgement.

This pathway assessment is a generic analysis and its results are not meant to be directly applied to any existing or future low-level waste disposal facility. It is recognized that pathway identification and assessment is a highly site-specific activity dependent on a large number of factors including (1) identification of current and future mechanisms and locations of potential human exposure to radionuclides; (2) identification of communications between the various media of radionuclide transport; (3) identification and assessment of the likelihood of various events and circumstances that lead to the release, transport, and transfer between media of radionuclides; and (4) identification of physical features and quantification of physical properties and parameters that promote or inhibit the migration of radionuclides. When site-specific data are considered the ranking of pathways may differ from the results of the generic analysis presented here. The existence or nonexistence of certain features and circumstances may allow some of the transfer links between media to be broken. This could allow additional pathways to be eliminated from consideration. Also, pathways assigned a lower priority in the generic ranking may emerge as more important when site-specific data are considered. It is also emphasized that this report considers only individual doses and the ranking of pathways would likely be different if population doses were considered.

2.0 PATHWAY ASSESSMENT

A schematic diagram of the potential migration and exposure pathways for near-surface low-level waste disposal facilities is depicted in Figure 2-1 [Shipers, 1989]. This figure illustrates the large number of complex interactions that can exist during the transport of radionuclides in the environment. These interactions are summarized in matrix form in Figure 2-2 where each of the blocks in the matrix indicates the potential for transfer of radionuclides between the media listed on the associated row and column of the matrix. An empty block indicates that no transfer of radionuclides between the media may occur. A downward pointing arrow indicates transfer of radionuclides from the medium listed on the row to the medium listed in the column. An upward pointing arrow indicates radionuclide transfer from the column to the row. A double headed arrow indicates a bidirectional transfer between the associated media.

Migration and exposure pathways may be constructed using Figure 2-2 by combining media with valid radionuclide transfer links. Each of the pathways must begin with a valid source-to-medium link and end with a valid medium-to-man link. If media were allowed to be repeated within a single pathway, an infinite number of pathways for the transport of radionuclides from the source to man could be constructed. When the construction procedure is constrained to allow a medium to appear no more than once in a given pathway, over 8000 migration and exposure pathways can be constructed using the 9 media and interactions shown in Figure 2-2. More pathways exist than is reasonable or possible to analyze during a performance assessment of a low-level waste disposal facility. Therefore, in this document these pathways are generically prioritized to identify those most important in a performance assessment.

Recycling can be eliminated by recalling that the primary objective of this generic analysis is to identify the most significant migration and exposure pathways in terms of dose to the general population. This implies that the media that result in the highest potential dose to man should be identified. These maximum doses should occur by human exposure to media in which the radionuclides are originally released. This occurs because it is unlikely that all of the radionuclides transferred from one medium to another can be returned to the original medium. A dilution effect occurs because 100% of the contaminants are not normally transferred from one medium to another. Consideration of parallel pathways in the performance assessment also lessens the need to consider recycling because the effects of contamination in both the medium of original release and the other media contaminated along the pathway are considered simultaneously. To illustrate the interaction of the consideration of parallel pathways with the assumption of no recycling, the case of atmospheric transport will be examined. Under the conditions of the stated criteria, deposition of radionuclides to soil and

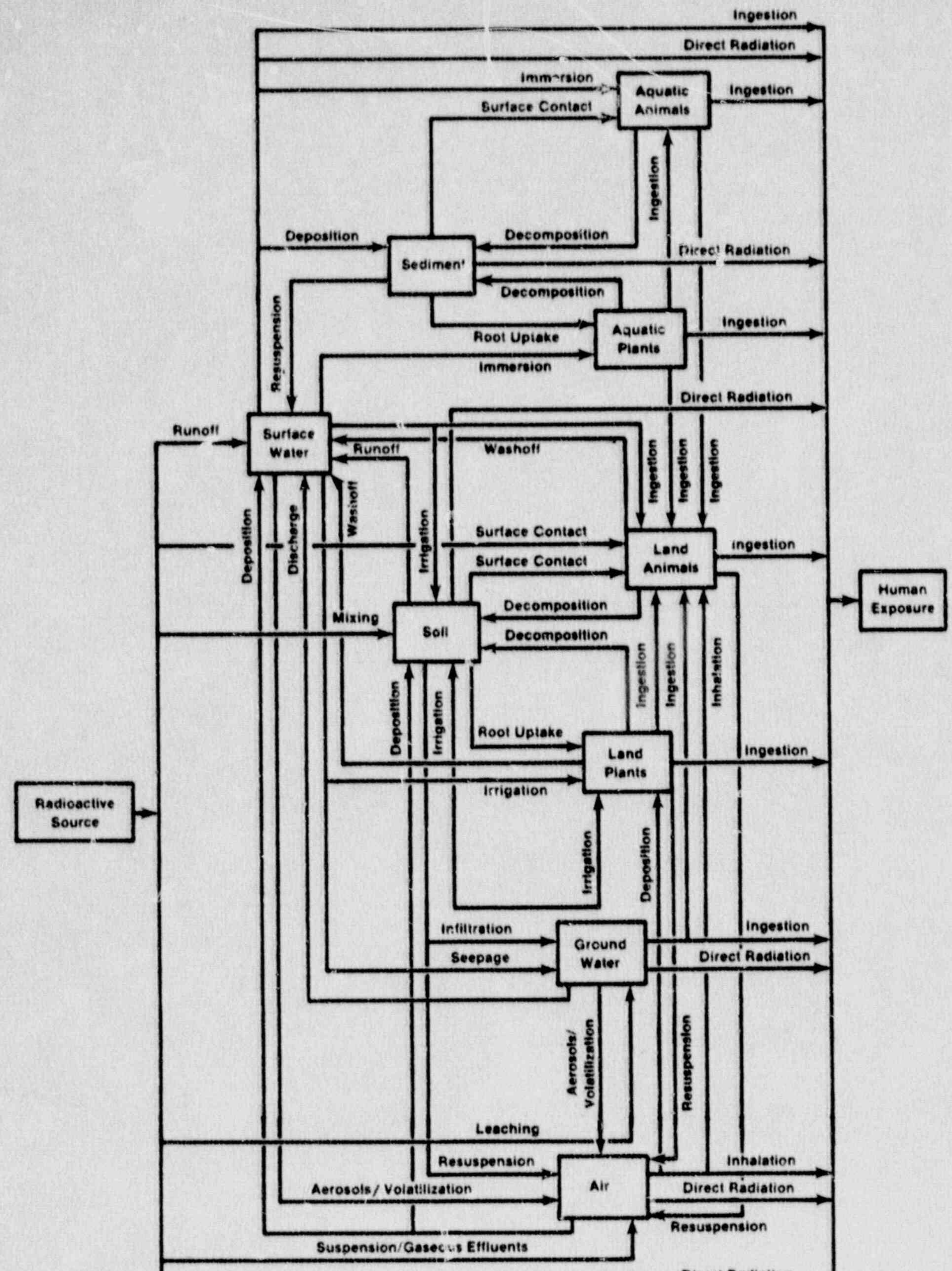

Figure 2-1 Potential Migration and Exposure Pathways for Near-Surface Low-Level Waste Disposal Facilities [Shipers, 1989]

	air	surface water	groundwater	soil	land plants	land animals	sediment	aquatic plants	aquatic animals	man
aquatic animals										↓
aquatic plants									↓	↓
sediment								↕	↕	↓
land animals								↑	↕	↓
land plants						↕			↓	↓
soil					↕	↕				↓
groundwater				↕	↓	↓				↓
surface water			↕	↕	↕	↕	↕	↕	↕	↓
air		↕	↑	↕	↕	↕				↓
source	↓	↓	↓	↓	↓	↓				↓

Figure 2-2 Interaction Matrix for Transport of Radionuclides in the Environment

resuspension of the same radionuclides would not be considered because maximum dose is expected to occur from exposure to the air prior to deposition unless it is a long term deposition resulting in significant deposition of radionuclides to soil. However, resuspension of soils that were contaminated from other sources, such as irrigation with contaminated ground water, would be considered in the calculation of total dose from inhalation of and immersion in contaminated air.

The detailed discussion of the number of connected media in a pathway considered in this analysis is limited to a maximum of three intermediate media between the release of radionuclides at the source and exposure to man. It is necessary to consider a few pathways with four and five intermediate media to complete the propagation of radionuclides through the food chain. The limitation of the length of migration and exposure pathways is consistent with previous analyses of the transport of radionuclides in the environment [Soldat et al. 1974; NRC, 1981c; Helton and Kaestner, 1981; McKenzie et al., 1984; Kennedy et al., 1986]. Longer pathways of up to 9 intermediate nonrepeated media can be constructed but it is doubtful that any of these would be identified as "important." As stated earlier, each medium in the pathway generally retains some portion of radionuclides as transfers to other media occur. As the number of media in a pathway increases, this dilution effect increases and the potential consequences of human exposure at the end of the pathway are reduced. It should be noted, however, that bioaccumulation can cause the highest concentrations to exist at the top of some food chains. Also, generally all media, with the exception of biota, tend to dilute and disperse the contamination. This dispersion and dilution continues until the contamination is uniformly distributed in the medium and steady state is reached. The resulting level of contamination in the medium depends greatly upon its effective volume. Media with large effective volumes such as the atmosphere and large bodies of water can redistribute the radionuclides to essentially background levels. Because the migration of radionuclides along the pathways does not occur instantaneously, the time required for transport to man increases as the number of intermediate media in the pathway increases. The increased transport time allows for additional radioactive decay as well as additional dilution and dispersion of the contaminants. In general, the more important pathways can be expected to be those associated with exposure to the medium of initial release of radionuclides or those pathways with fewer intermediate media. The consideration of parallel pathways during performance assessment will insure that exposure from all media is considered.

2.1 Assessment Strategy

The migration and exposure pathways were not ranked by performing a formal risk analysis. As previously stated, no numerical values of event probabilities or consequences were calculated as a part of the pathway assessment. Instead, a subjective two-level ranking system (low, high) was used to qualify both the likelihood of events and circumstances that may lead to the transport of radionuclides along a pathway and the level of significance to the general population of exposure to radionuclides that may be transported along a pathway. The relative levels of likelihood and significance of radionuclide transport along a pathway were assigned based upon previous assessments, simple calculations, and expert judgment.

Consideration of the magnitude and severity of the controlling events and circumstances, the potential time of exposure to the waste, the quantities of waste likely to be available for transport, and the mechanisms of transport and exposure were used to rank the significance of transfer along a link. The evaluation was begun with consideration of simple one-medium pathways. Each of the source-to-medium and medium-to-man links in these pathways was examined individually. Identification of the events and circumstances required for transfer of radionuclides was performed for each link. This identification process included consideration of the physical features, properties, and processes required for the transfer to occur. This activity allowed the factors that control transfer along the links to be identified. Examination of the controlling factors allowed the relative likelihood and significance of the transfer of contamination between the media to be ranked. The likelihood of transfer along a link was ranked by consideration of the likelihood of occurrence of the controlling events and circumstances.

Migration and exposure pathways were ranked by tracking and accumulating likelihoods and significances of the individual links. The likelihood of each link was tracked independently from the significance. A "minimum value" accumulation procedure was used during the ranking process. For example, when a low likelihood link was followed by a high likelihood link, a low likelihood was assigned for the pathway. This ranking procedure results in the determination of a relative likelihood and significance for the transport of radionuclides along each pathway considered.

Some additional consideration should be given to the accumulation of low rankings during the pathways assessment. When a low likelihood link is followed by another low likelihood link, the result is a "very low" likelihood that the transfer of radionuclides will occur along the pathway. This same effect will occur when low significance links are considered in series. The accumulation of high rankings does not exhibit this accumulating effect. Since the links occur in series, two high likelihood links do not result in "very high" likelihood that radionuclides will be transported along the pathway. After the first transfer occurs, the likelihood of an occurrence of a second transfer (and transfer along the pathway) remains at a high level. Similarly for significance, if all of the contaminants are passed through series of "high" links, the significance remains at a high level since additional contamination is not introduced into the pathway.

The results of the one-medium ranking were directly applied in analyzing the more complex two-media pathways. The likelihood and significance levels developed for the source-to-medium and medium-to-man links during the one-medium ranking were carried over and applied to the links in the two-media pathways. The additional medium-to-medium links in the two-media pathways were then examined. As before, the events and circumstances controlling transfer along the links were identified and relative levels of likelihood and significance assigned. The existence and analysis of parallel pathways during performance assessment was considered during the assignment of levels of significance. In some cases, the level of significance of a link was assigned a lower value because of the existence of a potentially higher consequence parallel pathway. The minimum-value accumulation procedure was again used to establish the likelihood and significance of the two-media pathways. The likelihood and significance levels used for the two-media links were then carried over to the three-media pathways and the evaluation and ranking process was repeated.

It is necessary to include certain regional and climatic considerations during the evaluation and ranking of the pathway links. Rainfall amounts and temperature ranges can affect the fauna and flora present, amounts of infiltration, and likelihood of potential disruptive events such as frost heave and agricultural intrusion. Regional conditions such as depth to the water table, proximity to surface water, and surface soil types and properties can have a significant effect on the likelihood and significance of radionuclide migration in the environment. The likelihood and significance levels assigned during the generic ranking were qualified in terms of these regional and climatic considerations. A summary of potential important migration and exposure pathways for two different types of climatic regions is included in Section 3 of this document.

2.2 Direct Exposure Pathway

One direct source-to-man pathway exists. The exposure mechanism for this pathway is direct gamma radiation as a result of proximity to and/or contact with the waste. Human intrusion into the site is required for significant doses to occur via this pathway. The future actions of individuals are very difficult to predict. The likelihood of intrusion into the site is highly dependent upon potential future uses of the site. Factors such as climatic conditions and their compatability with agricultural activities, existence of natural resources in the vicinity of the disposal facility, locations of nearby population centers and their projected growth, and current and projected uses of surrounding land area may be used to assist in predicting the likelihood of future human intrusion into the site. The technical requirements of 10 CFR Part 61.50 explicitly state that the disposal facility should be sited to minimize effects of future population growth and development. These technical requirements also state that the facility should be located away from known natural resources whose future exploitation could adversely effect the ability of the site to isolate low-level waste. Even though the siting criteria in 10 CFR 61.50 attempt to minimize the likelihood of future human intrusion, scenarios of inadvertent human intrusion are normally postulated as a part of performance assessment of low-level waste disposal facilities. Therefore, consideration of the activities of a future inadvertent intruder in performance assessment is appropriate even though human intrusion may not be likely.

Engineering and design options exist to minimize the potential for direct gamma radiation exposure from an intact disposal structure [NRC, 1981b]. Soil covers with sufficient thicknesses to provide adequate shielding to lower exposure rates to background levels for an individual immediately adjacent to the disposal structure are easily designed and cost effective. While the use of concrete in engineered structures provides additional shielding and integrity to the disposal structure, it should be noted that a soil cover and its shielding advantages are retained even for above-grade disposal. The operational practice of layering Class B waste over the higher activity and longer half-life Class C waste provides the potential for additional shielding and intruder protection. An institutional control period of up to 100 years is mandated in 10 CFR Part 61.7 to control access to the disposal facility. This provision is designed to allow disposal of Class A and B wastes without the need for special intrusion protection since it will allow sufficient time for the radioactivity of these wastes to decay to acceptable levels during the control period. Any human intrusion events that occur during the institutional control period should be of very short duration. The combination of these factors results in the assignment of a low likelihood and significance to the direct source-to-man pathway for the undisturbed performance of the disposal facility.

Events which disrupt integrity of shielding or expose waste at the surface can potentially result in high direct gamma doses to a human intruder. A high significance was assigned to the source-to-man pathway under these disturbed conditions. Naturally occurring events that can disrupt the integrity of the disposal structure were assigned a low likelihood of occurrence after consideration of several factors. The technical requirements of 10 CFR Part 61.50 state that the disposal site should be located to minimize chances of disruption resulting from both tectonic processes such as seismic activity, volcanism, folding, and faulting and surface processes like weathering, landsliding, and slumping. In addition, the site should be well drained and upstream drainage minimized. While some surface processes such as erosion are climate dependent, 10 CFR Part 61.51 requires that surface features must direct surface water drainage away from disposal units at velocities and gradients which will not cause erosion and the need for future maintenance. Covers must be designed to reduce infiltration and the disposal site designed to reduce contact of water with the waste. Also, the closure and observation periods of the disposal facility life cycle provide the opportunity to discover and correct any design or natural features that can potentially degrade the long-term integrity of the disposal facility.

The likelihood of significant releases of radionuclides resulting from settlement or subsidence of the containment structure is low [Denson et al., 1987, 1988]. The use of engineered structures, backfilling to minimize void space, and compaction of caps and soil covers all reduce the likelihood of this type of disruptive event. The operational practice of segregating structurally unstable Class A waste from stable Class B and C waste would help minimize the consequences resulting from settlement or subsidence of the containment structure. The institutional control period should allow sufficient time for the decay of the shorter half-life Class A wastes.

As previously discussed, the activities of human intruders into the disposal facility are difficult to predict. Certain human intruder activities such as drilling, excavation and construction, and agriculture can seriously disrupt the integrity of the containment structure and can move significant amounts of waste to the surface or near-surface. The likelihood of some of these activities is climate dependent. For example, the availability of adequate amounts of water and the existence of a moderate temperature range could encourage occupation rather than just exploration of the site. Since it is appropriate to consider the activities of human intruders into the disposal facility in performance assessment, a high likelihood of exposure was assigned to the source-to-man pathway for the intruder-disturbed performance of the facility.

2.3 One-Medium Pathways

Table 2-1 shows the six pathways with one intermediate medium between the source and man which may be constructed using interactions shown in Figure 2-2. These pathways are discussed in their order of appearance in the table. For each pathway, the discussion and assignment of the likelihood and significance associated with radionuclide transport across the source-to-medium link is followed by a parallel evaluation of the medium-to-man link. Events and circumstances related to the undisturbed and disturbed performance of the disposal facility are discussed. As in the preceding section, events which result in the disruption of the containment structure and/or expose waste at or near the surface are divided into two categories: naturally occurring events and intruder activities. For the reasons presented in discussion of the disruptive events in the preceding section, all naturally occurring disruptive events were assigned a low likelihood of occurrence and all intruder-induced disruptive events were assigned a high likelihood.

Source-to-Air Link

The presence of free contaminated gases in the containment structure may result in radionuclides entering the atmosphere by diffusion through the containment structure and soil cover. Free contaminated gases may be introduced in the containment structure as a result of failure of disposal canisters of gaseous waste (if gaseous waste exists at the facility) or decomposition of organic wastes. The radionuclides expected to be associated with decomposition gases are tritium and carbon-14 [Wild et al., 1981]. The quantities of radionuclide tagged decomposition gases at a disposal facility are a function of amounts and distribution of the organic wastes present. The types and quantities of gaseous and organic waste expected to exist at a disposal facility are site-specific considerations. Because some amount of gaseous and/or organic waste is expected to exist at all disposal facilities, and if they exist, some canister failure and/or decomposition will occur, a high likelihood of transfer of radionuclides was assigned to the source-to-air link in this generic study. Since the amounts of this type of waste and the resulting contamination is expected to be comparatively small [Wild, 1981], a low significance of transfer was assigned to this link.

An event that disrupts the integrity of the containment structure and exposes waste at the surface can result in significant atmospheric contamination. At the time of the disruptive event, contaminants could be injected into the atmosphere. Ongoing atmospheric contamination could result in the suspension of waste particles by near-surface turbulent eddies. The amount of contamination introduced into the atmosphere by suspension is highly dependent on the wind velocity [Till and Meyer, 1983]. Since significant quantities of radionuclides can be introduced into the atmosphere and the potential for long-term contamination exists due to suspension, a high significance of radionuclide transport along the source-to-air link was assigned for the disturbed performance of the disposal facility. The likelihood of transport along this link is dependent upon whether the containment structure integrity is disrupted by a naturally occurring event such as an earthquake or erosion (low likelihood) or intruder activity such as construction or growing of crops (high likelihood).

Air-to-Man Link

Human exposure may result from inhalation and immersion in contaminated air. The likelihood and consequence of human exposure to airborne radionuclides is dependent on a number of factors including: location of receptor, prevailing wind directions and speeds, and amount and duration of contamination. These are all site-specific factors, but a likelihood and significance of transport along the air-to-man link was assigned based upon some generic considerations. In all cases, a high significance of exposure to airborne radionuclides was assigned because significant health effects resulting from long-term exposure even at low concentrations. The potential for minor health effects which results from limited exposure to small quantities of radionuclides for short periods is accounted for by allowing the low significance associated with the initial release to be propagated through the pathway by the "minimum value" accumulation procedure. For the introduction of radionuclides into the atmosphere by gaseous diffusion, a low likelihood of exposure of an offsite receptor was assigned to the air-to-man link because it is unlikely that the small amounts of gases assumed to be present would be transported significant distances and result in measurable atmospheric contamination. A high likelihood of exposure was assigned to the link for an onsite receptor since gaseous and/or organic wastes were assumed to exist at the disposal facility and the likelihood of exposure increases as the receptor approaches the source of the atmospheric contamination. Since it is not possible to justify ignoring the doses that can result from human exposure to the potentially large amounts and extended periods of airborne contamination possible when waste is exposed at the surface, a high likelihood of transfer along the air-to-man link was assigned to both onsite and offsite receptor locations for the disturbed performance of the disposal facility.

Source-to-Soil Link

The mechanisms for transport of radionuclides along the soil pathway are very similar to those discussed for the direct exposure to waste pathway. Human exposure via this pathway results from direct gamma radiation due to proximity to and/or contact with a soil and waste mixture. While soil and waste are normally mixed during the backfill and closure processes of site operation, the containment structure and soil cover should provide adequate shielding for the undisturbed performance of the disposal facility. A low likelihood and significance of radionuclide transport were assigned to the source-to-soil link of this pathway under these conditions. If the containment structure and soil cover are disturbed and waste is exposed, surface soil could mix with the waste. Potentially large amounts of waste may be introduced into soil in this manner. Thus, a high level of significance for radionuclide transport was assigned to the source-to-soil link for the disturbed performance of the disposal facility. Events resulting in the disruption of the containment structure have been previously discussed and, as before, a low likelihood of transport along the source-to-soil link was assigned for naturally occurring events and a high likelihood was assigned to the link for intruder induced disruption.

Soil-to-Man Link

Human intrusion into the disposal facility must occur before significant doses can result from the source-to-soil-to-man pathway because the contamination should remain in the immediate vicinity of the containment structure unless some intermediate medium is introduced to transport the soil and waste mixture. Since human intrusion is normally assumed as a part of performance assessment, a high likelihood for exposure to radionuclides was assigned to the soil-to-man link. High doses can result from exposure to a soil and waste mixture, especially if large amounts of waste are involved and/or the exposures are long-term. Even though these potentially high doses imply a high level of significance for the soil-to-man link, these doses should be less than those associated with the direct exposure pathway since the mixing results in dilution of the waste. Because parallel pathways will be considered and analyzed as a part of site performance assessment, a low significance was assigned to the soil-to-man link in this generic study. The waste (and thus the exposure) could be partitioned between the direct pathway and a soil and waste mixture in performance assessment, but exposure to the total inventory waste by both pathways should not be assumed and the doses summed because this would, in effect, double the amount of waste at the facility.

Source-to-Ground Water Link

Since the technical requirements of 10 CFR Part 61.50 state that the disposal facility should provide sufficient depth to the water table to prevent ground water intrusion into the containment structure, the primary mechanism for introduction of radionuclides into ground water is transport through the unsaturated zone. The infiltration rate into the containment structure depends upon a number of site-specific factors including amounts of precipitation, runoff, and evapotranspiration; types and quantities of flora present; and soil properties and modification of properties as a result of plant and animal activities. The primary source for infiltration at the disposal facility should be precipitation. Infiltration into the containment structure as a result of standing surface water should not be significant at the disposal facility because the technical requirements of 10 CFR Part 61.50 state that the site should be generally well drained and free from areas of flooding or frequent ponding. Federal Code 10 CFR Part 61.51 requires that covers be designed to minimize infiltration and surface features must direct surface water drainage away from the disposal units at velocities and gradients that will not cause erosion.

Once water enters the containment structure radionuclides may be mobilized by processes such as dissolution, diffusion, desorption, biodegradation, and ion exchange. The contaminated ground water is then transported downward through the unsaturated zone to the saturated zone. Again, the extent of ground-water contamination is highly dependent upon a number of site-specific factors including: soil properties such as hydraulic conductivity, moisture content, sorptive capacity, and geochemical conditions; physical characteristics such as infiltration rates and depth to water table; and existence of certain physical features such as fractures. Since concrete is a permeable material, some infiltration can be expected even for engineered structures. These rates of infiltration can increase with time as a result of degradation of the concrete. Because the infiltration rate is a highly regional and climate dependent parameter, it is unlikely that it can be held at zero for extended periods after the closure of a disposal facility [DOE, 1988]. Thus, a high likelihood of transport of radionuclides was assigned to the source-to-ground water link for the undisturbed site performance. Since large amounts of contaminants can potentially be introduced into ground water and the process can potentially result in long term contamination, a high consequence of transport along the source-to-ground water link was assigned. Events that disrupt the containment structure and/or soil cover enhance the likelihood and potential consequences of introduction of radionuclides into ground water. Thus, high likelihood and consequence levels were also assigned to this link for the disturbed performance of the disposal facility.

Ground Water-to-Man Link

Once radionuclides are introduced into ground water, human exposure may result from use of ground water withdrawn from a well located in the contaminated aquifer. Exposure may result from ingestion of, immersion in, and/or proximity to water used for household, agricultural, and other purposes. Because this exposure (both internal and external) can be long term and cumulative due to use of ground water with high radionuclide concentrations, the consequence of radionuclide transport in the ground water-to-man link was assumed to be high. Consideration of potential consequences resulting from human exposures to contaminated ground water is an appropriate part of performance assessment of low-level waste disposal facilities. The existence of a withdrawal well in a contaminated aquifer and human activity associated with its use are normally assumed during performance assessment. Because of these considerations, a high likelihood of transport of radionuclides along the ground water-to-man link was assumed. It should be noted that as a withdrawal well is moved farther from the source of the contamination, the transport time increases resulting in additional radioactive decay. The additional distance travelled also increases dispersion, retardation, and dilution of the contaminants. Even though these factors may reduce the dose resulting from exposure to radionuclides in ground water, the high likelihood and significance levels assigned to the ground water-to-man link were applied to both onsite and offsite receptor locations.

Source-to-Biota Links

The pathways associated with land animal and plant intrusion into a disposal facility are considered simultaneously. While the types and quantities of plant and animal life expected to be present at the disposal facility are highly regional and climate dependent parameters, some form of biota will be present at all sites. Most burrowing animals and plant roots have been observed to penetrate to a depth of less than 2 meters below surface at both arid [McKenzie, et al., 1982] and humid [McKenzie, et al., 1983] sites. Engineering and design measures can be implemented to minimize the likelihood and potential impact of plant and animal intrusion. The use of engineered structures provides an additional barrier to plant and animal intrusion. The operational practice of layering lower activity Class B waste over Class C waste, when considered in conjunction with the time allowed for radioactive decay during the institutional control period, provides an additional barrier. Due to these considerations, a low likelihood and consequence of radionuclide transport was assigned to the source-to-land plants and source-to-land animals links for the undisturbed performance of the disposal facility.

If an event which disrupts the integrity of the containment structure and/or soil cover occurs, the potential for direct contact of plant and animal intruders with waste exists. As before, a low likelihood of occurrence was assigned to naturally occurring disruptive events and a high likelihood assigned to intruder induced disruptive events. If the disruptive event exposes waste at or near the surface, plants may become contaminated due to root uptake. It is unlikely that most plants will find sufficient nutrients within the waste alone for survival. For this reason, the transport of radionuclides to plants via root uptake is more appropriately represented by transfer from a soil and waste mixture. Transfer of radionuclides by this mechanism is considered as a part of the two-media pathways. Therefore, a low significance of transport along the source-to-land plants link was assigned for the disturbed performance of the disposal facility. Animals may become contaminated by both ingestion of and surface contact with the waste. Again, it is unlikely that most animals will find sufficient nutrients within the waste for survival, especially after considering that a delay period is required before disruptive events can occur. Food preparation techniques such as washing and skinning are likely to minimize effects of surface contamination [Till and Meyer, 1983]. Since transfer of radionuclides by ingestion is more appropriately represented by the plants-to-animals link (which is considered in Section 2.5) and the quantities and effects of surface contamination are likely to be limited, a low significance was assigned to transfer along the source-to-land animals link for the disturbed performance of the site.

Biota-to-Man Links

The transfer of radionuclides from plants and animals to man occurs as a result of ingestion of contaminated food products. If radionuclides enter the food chain it is appropriate to assume that at some point they will be consumed by man, thus a high likelihood of exposure was assigned to both the land plants-to-man and land animals-to-man links. Biota tend to concentrate certain radionuclides. This bioaccumulation effect can be decreased by the time delay required for contaminants to travel through the food chain, especially for radionuclides with a comparatively short half-life. Cooking also tends to reduce the level of contamination in food products, but the amount of this reduction is specific to the cooking process and difficult to quantify [Till and Meyer, 1983]. Since the potential exists for high levels of contamination in food products due to bioaccumulation and exposure may result from potentially long-term human consumption of contaminated products, a high significance was assigned to the transfer of radionuclides along the land plants-to-man and land animals-to-man links. The high likelihood and consequence levels assigned to these exposure links are equally applicable to both onsite and offsite receptors.

Source-to-Surface Water Link

No mechanism exists, with the possible exception of bathtubbing, for the direct introduction of radionuclides into surface water for an undisturbed containment structure. The bathtubbing scenario is based upon the assumption that the low hydraulic conductivity of the medium surrounding the containment structure results in the structure being filled with water by infiltration. Once water is present in the containment structure, radionuclides are mobilized by chemical processes associated with the rinsing and leaching of the waste. Since the water is assumed to be static within the containment structure, high concentrations can result from the potentially long-term contact of the water with the waste. Subsequent precipitation and infiltration result in containment structure overflow, runoff, and surface water contamination. This scenario is normally associated with some event, such as subsidence or settlement, that disrupts the integrity of the containment structure and enhances infiltration. As previously discussed in relation to the direct exposure pathway, design and engineering measures exist to minimize the likelihood of occurrence of the disruptive events which are normally associated with bathtubbing. Containment structures and their soil covers are designed to minimize infiltration. Backfills are included to minimize void space. In humid environments backfills and drains are designed to keep the containment structure well drained and free of accumulated water. The stability requirements and engineered structures minimize the likelihood of subsidence or collapse that would enhance infiltration. These factors combine to make the likelihood of the occurrence of bathtubbing at an undisturbed site low. Thus, a low likelihood and significance of transport along the source-to-surface water link was assigned for the undisturbed performance of the disposal facility.

Events that disrupt the integrity of the containment structure and expose waste at the surface provide an opportunity for the introduction of radionuclides into surface water. This contamination may result from direct contact with waste brought to the surface or bathtubbing due to increased infiltration. Precipitation is the primary source of surface water contaminated in these manners. The technical requirements of 10 CFR Part 61.50 specify that the disposal site should be free of areas of flooding and ponding. Even though 10 CFR Part 61.50 requires that the site be well drained and designed to minimize upstream drainage, it was assumed in this analysis that some runoff would come in contact with any exposed waste. Under this assumption, likelihoods consistent with those previously discussed for disruptive events were assigned for the transfer of radionuclides along the source-to-surface water link. A low likelihood was assigned for naturally occurring disruptive events and a high likelihood was assigned for disruptive events associated with the activities of intruders.

After surface water comes in contact with waste, radionuclides are mobilized by the same chemical processes discussed in relation to ground water pathway. The severity of the contamination depends upon a number of factors including the amounts of waste exposed, chemical properties of waste, amount of water contacting waste, and the duration of water contact. The last two factors are highly regional and climate dependent. Although the potential for significant contamination of surface water resulting from disruptive events will vary widely from site to site, a high significance was assigned to transport along the source-to-surface water link because of the potential for the introduction of large amounts of radionuclides over long periods of time in this medium.

Surface Water-to-Man Link

Man may be exposed to radiation by immersion in, proximity to, and/or ingestion of contaminated surface water. The likelihood of this type of human exposure is primarily dependent upon proximity of continuously available surface water (ponds, lakes, streams, etc.) to the disposal facility. This is a site-specific consideration. If significant amounts of surface water are present in the vicinity of the site, it is normally assumed in a performance assessment that man will use this water for drinking and other purposes unless some defensible site-specific reason eliminating exposure by this means can be established. To allow human exposure by this mechanism, a high likelihood was assigned to the surface water-to-man link for both onsite and offsite receptors. Since the concentrations of radionuclides in surface water can be high and human exposure is expected to be long-term and cumulative, a high level of significance for transfer was assigned for the surface water-to-man link.

2.4 Two-Media Pathways

A total of 32 migration and exposure pathways with two intermediate media between the source and man may be constructed using the interactions shown in Figure 2-2. These pathways are listed in Table 2-2. The likelihood and significance of the events and circumstances leading to transfer of radionuclides across the source-to-medium and the majority of the medium-to-man links were discussed in Section 2.3. The likelihood and significance levels assigned to these links are carried over to the two-media pathways and their discussion is not repeated in this section. Discussions of the two-media pathways are presented in their order of appearance in Table 2-2.

Air-to-Medium Links

The two-media pathways with air as the medium of initial contamination become important when offsite receptors are considered. Once the site is disturbed, atmospheric transport provides a mechanism to move radionuclides offsite. Even though the extent of this type of contamination is highly dependent on site-specific factors such as prevailing wind direction and speed, a high likelihood exists that at some time after waste is exposed, site conditions will result in contaminants being moved offsite and deposited on soils, surface waters, land plants, and land animals. Additional land animal contamination may also occur due to inhalation of airborne radionuclides. In this study, a high likelihood of transfer of radionuclides from air to soil, biota, and surface water was assumed. The severity of the significance of transfer of radionuclides from the atmosphere to these four media is highly dependent on the amount of contamination initially in the air, prevailing weather conditions, and the length of introduction of contamination into air. The last factor becomes important because of the potential for radionuclides to accumulate in the soil and biota. A high significance was assigned to the transfer of radionuclides from the atmosphere to the soil and land plants to allow the effects of the severity of the initial release to propagate through the food chain pathways. A low significance was assigned to the transfer of radionuclides from air to surface water because of dilution, and from air-to-land animals because this pathway is insignificant compared to the pathway containing contaminated food for land animal consumption.

The biota-to-man and surface water-to-man links were assigned high likelihood and consequence in the preceding section. These likelihood and significance levels are equally applicable to the two-media pathways. Recall that the soil-to-man link was previously assigned a low significance because of parallel pathway considerations. For a disruptive event with an onsite intruder, it was stated that the direct source-to-man pathway would result in higher doses. This direct source-to-man exposure pathway does not exist for an offsite receptor, so a high significance of transfer along the soil-to-man link was assigned under these conditions.

Even though likelihood of transfer of radionuclides from air to biota remains at a high level for an onsite receptor, it is appropriate to assign a low significance to the air-to-soil and air-to-surface water links in this case. The two-media pathways associated with these links have a corresponding one-medium pathway in which radionuclides may be directly introduced into the secondary medium. As previously stated, the doses for an onsite receptor should be higher for exposure to original medium of contamination due to time delay, dilution, dispersion, and transfer effects associated with transport in the secondary media. Since parallel pathways will be considered during performance assessment, lower significance was assigned to these secondary means of exposure. The significance level for human exposure from plants and animals remains high because air provides an effective means for the introduction of radionuclides into the food chain even for an onsite receptor.

Soil-to-Medium Links

Once contaminants are introduced into onsite surface soils by a disruptive event, the likelihood that radionuclides will be transferred to air, ground water, surface water, and the food chain is high. The mechanisms associated with the transfer of radionuclides from soil to these other media are the same as those discussed in the previous section for the direct introduction of contaminants into the associated medium. High consequence one-medium migration and exposure pathways exist for air, ground water, and surface water. Since parallel pathways are considered as part of performance assessment and higher levels of contamination (and significance) should exist for the medium of original contamination, low consequence of radionuclide transport was assigned for the soil-to-air, soil-to-ground water, and soil-to-surface water links. The radionuclide inventory must be partitioned between the various media for transport, so that it is more conservative to introduce the contamination directly from the source into a medium.

Contaminated soil provides a viable mechanism for radionuclides to enter the food chain. Root uptake is a primary means of plant contamination. Since bioaccumulation in plants can result in concentrations above soil levels for certain radionuclides, a high significance was assigned to the soil-to-land plants link. The mechanism for transfer of radionuclides from the soil to land animals are the same as those discussed in relation with the source-to-land animals link. The primary transfer mechanism is surface contact. Very small potential exists for animal ingestion of contaminated soils. As discussed before, preparation procedures such as washing and skinning will limit the amounts of contamination transferred to man. Any human exposure that results from proximity to and/or contact with surface contaminated animals will be less than exposures resulting from proximity to and/or contact with the contaminated soil. Due to these factors, a low significance of transfer of radionuclides was assigned to the soil-to-land animals link. Since transfer from the soil to the secondary medium provides a mechanism for transport of radionuclides to offsite locations, the likelihood and consequence levels associated with these links are equally applicable to both onsite and offsite receptors. It should be noted, however, that higher doses (and significances) can generally be expected for an onsite receptor.

Ground Water-to-Medium Links

The ability of ground water to transfer contaminants to other media is dependent upon the existence of a means of communication between the media. The withdrawal and use of ground water from a well located in a contaminated aquifer provides a mechanism for the transfer of radionuclides to the air, soil, and food chain. The existence of natural flora and fauna is highly site-specific, but cultivated crops and domestic animals are normally assumed to exist during a performance assessment. Agricultural activity associated with the use of ground water from a contaminated well is normally considered in performance assessment. Thus a high likelihood of transport was assigned to the ground water-to-air, ground water-to-soil, and ground water-to-biota links. Existence of a discharge location from the contaminated aquifer is necessary for radionuclides to be transferred to surface water. The location of discharge points is a site-specific consideration, but if surface water exists a recharge or discharge communication is normally assumed between the surface water and the uppermost aquifer. This uppermost aquifer will normally be contaminated first as a result of radionuclide migration from a low-level waste disposal facility. In this study, a high likelihood of transfer of radionuclides from ground water-to-surface water was assumed. The likelihood can be reduced on a site-specific basis if no surface water exists or if the likelihood of discharge from the potentially contaminated aquifer is low.

Once contaminated ground water is withdrawn from a well and exposed at the surface, radionuclides may be transferred to the atmosphere. This transfer may occur as a result of volatilization and/or the production of contaminated aerosols. The amounts of volatile species that are likely to exist in ground water is site-specific and dependent on the initial inventory in the disposal facility. The amounts of these species were assumed to be small in this study. Therefore, a low significance of transport by volatilization was assigned. Contaminated aerosols may be introduced into the atmosphere by both agricultural activities such as irrigation and household activities such as showering and cooking. The amounts of contamination introduced into the atmosphere by these mechanisms are expected to be comparatively small. The human exposure time to this type of airborne contamination is also expected to be limited. Thus, a low significance was assigned to the transport of radionuclides as aerosols. This, when considered in conjunction with the low significance associated with volatilization, resulted in a low significance for the transfer of radionuclides along the ground water-to-air link.

Irrigation with contaminated ground water provides means for radionuclides to enter both the soil and land plants. Radionuclides may enter the soils from ground water as a result of chemical processes such as sorption, ion exchange, and/or precipitation. Evaporation of irrigation water can result in the deposition of radionuclides in soils. Irrigation with contaminated ground water allows radionuclides to enter plants by deposition on the plant surface or root uptake. The effects of transfer to both soil and plants are potentially long-term and cumulative. Concentrations of radionuclides in these media can become higher than those in the irrigation ground water. Due to these considerations, a high consequence of transfer of radionuclides was assigned to the ground water-to-soil and ground water-to-land plants links. Contaminated ground water used for watering can result in radionuclide transfer to both domestic and wild animals. Again, the effects of this type of exposure are both potentially long-term and cumulative. Bioaccumulation can also result in radionuclide concentrations higher than those in the ground water. A high significance of transport of radionuclides was assigned to the ground water-to-land animals link.

When contaminated ground water discharges into free surface water, dilution normally occurs. In the worst case of discharge, a spring, the radionuclide concentration in the water remains the same. Recall that human exposure results from ingestion of, immersion in, and/or proximity to contaminated water. Although the existence of surface water and the corresponding dilution factor near a low-level waste disposal facility are site specific, a high level of significance was assigned to the ground water-to-surface water link in this generic analysis.

The likelihood and significance levels previously assigned to the medium-to-man links may be applied to the ground water driven two-media pathways with one exception: the soil-to-man link. In the case of undisturbed performance of the disposal facility or for an offsite receptor, the pathway associated with this link provides a means for human exposure to direct gamma radiation which is not accounted for by any other pathway. High significance exposures along the direct source-to-man pathway only occur to an onsite receptor after the disruption of the containment structure and/or soil cover. Thus, a high significance was assigned to the soil-to-man link when the disposal facility is undisturbed or an offsite receptor is considered. It should be noted that for a disturbed site with an onsite receptor, the significance of the direct exposure to waste pathway would outweigh this two-media pathway.

Biota-to-Medium Links

The links from source-to-land plants and source-to-land animals have been previously discussed and assigned a low significance. Since the consequence of transport is propagated through a pathway by the "minimum value" accumulation procedure, a low significance results for the 10 two-media pathways with land plants and land animals as the media of original radionuclide release. Since the objective of this document is to identify the important migration and exposure pathways for low-level waste disposal facilities, the biota-driven two-media pathways will not be discussed further.

Surface Water-to-Medium Links

Evaluation of the two-media pathways with surface water as the medium of original contamination is similar to that of the air driven two-media pathways. The surface-water-driven two-media pathways become important as when radionuclides are transported offsite and introduced into the food chain. Once surface water becomes contaminated by runoff after a disruptive event, the likelihood of contact with, and thus contamination of, other media is high because natural processes for the interaction of surface water with other media exist. Due to the existence of these natural communications, a high likelihood of transport of radionuclides was assigned to all eight of the surface water-to-medium links. The mechanisms for transfer of radionuclides from surface water-to-air are the same as those discussed in relation to the ground water-to-air link (volatilization, aerosols). As in the ground water case, quantities of radionuclides transported by and exposure times resulting from these mechanisms are expected to be small. Thus a low significance was assigned to the surface water-to-air link.

Both irrigation and natural processes such as flooding and runoff provide the opportunity for radionuclides to be transferred from contaminated surface water to the soil. As before, radionuclides can be transferred as a result of both chemical processes and evaporation. The resulting level of soil contamination is dependent upon the duration of contact with and the concentration of the contaminated surface water. Since this type of contamination is both cumulative and potentially long-term, soil concentrations can become higher than those in the contaminated surface water. To allow propagation of the consequences of the initial contamination and to consider potential effects of accumulation, a high consequence was assigned to the surface water-to-soil link. As in the source-to-air-to-soil-to-man pathway, the significance of the soil-to-man link in the surface water driven two-media pathways should be increased to high for an offsite receptor. In this case, the contaminated soil provides a means for human exposure to direct gamma radiation and allows radionuclides to be retained for long-term exposure. Since the integrity of the containment structure must be disrupted before radionuclides can be introduced into surface water, the direct source-to-man exposure pathway is of higher significance for an onsite receptor.

Radionuclides may be transferred from surface water to sediments by sorption, ion exchange, precipitation, and/or coprecipitation. The amount of radionuclide transfer to sediments is highly dependent on the concentration in the surrounding water and the sediment properties. A sediment functions primarily as a radionuclide source and sink for surface water in the aquatic system. A high significance was assigned to the surface water-to-sediment link to allow effects of the initial contamination to propagate through pathway.

Sediment-to-Man Link

The sediment-to-man link has not been previously discussed. The primary exposure mechanism for this link is direct gamma radiation resulting from surface contact with and/or proximity to contaminated sediments. Since the recreational use of significant bodies of surface water can be expected and these uses could include activities such as swimming and boating, the likelihood of human contact with or proximity to sediments is high. Thus, a high likelihood of exposure was assumed for the sediment-to-man link. Since the exposure time associated with the recreational activities is expected to be limited and due to the consideration of parallel pathways an individual participating in these activities will receive a dose from immersion in and proximity to the contaminated surface water, a low significance was assigned to the sediment-to-man link. It should be noted that the effects of contamination of flood plains and dry stream beds are accounted for in the source-to-surface water-to-soil-to-man pathway.

The interaction of surface water and ground water has been discussed in relation to the ground water-to-surface water link. Transfer of radionuclides between these media requires that a recharge or discharge location exists. As before, a high likelihood of transfer was assigned to the surface water-to-ground water link because even though the location of recharge is site specific, communication between existing surface water and the uppermost aquifer is likely. Recharge of ground water from contaminated surface water should result in dilution of the radionuclides. Thus, higher doses should result from direct exposure to and/or ingestion of the medium of initial contamination, surface water. Also, other more direct pathways than recharge exist for the contamination of ground water. These more direct and shorter pathways should have higher concentrations and higher potential consequences. Because it is necessary to partition the inventory of radionuclides available for transport between the various media of original release during the analysis of parallel pathways, these considerations lead to the assignment of a low significance to the surface water-to-ground water link.

The mechanisms for transfer of radionuclides from surface water-to-land plants and surface water-to-land animals are the same as those discussed in relation to the ground water driven two-media pathways. The primary difference that occurs when surface water is the medium of initial release results from the fact that the actions of man are not required to provide a means of transfer of radionuclides to the biota. While irrigation and watering can increase amount of transfer along links, they are not necessary for the transfer to occur. A high likelihood for the occurrence of radionuclide transfer along the surface water-to-land plants and surface water-to-land animals links was assigned. As before, due to the potential for bioaccumulation in biota and the potential for the long-term exposure of biotic media from surface water, a high significance was assigned with these links.

Radionuclides may be transferred to aquatic plants and animals as a result of their existence in contaminated surface water. The types and quantities of aquatic life are site specific. The level of contamination in aquatic life is dependent upon both the amounts of and length of exposure to radionuclides. Due to bioaccumulation, long-term exposures can result in biotic concentrations above the level present in the water. This effect is species and radionuclide dependent [Till and Meyer, 1983]. Despite the site-specific character of these links, a high significance was assigned for the transfer of radionuclides to aquatic life in this study. This allows an additional means for the effects of a release in surface water to propagate to man.

Aquatic Life-to-Man Links

Links between the aquatic food chain and man have not been previously discussed. Human exposure for these links occurs as a result of ingestion of contaminated food products. Because of limited types and amounts of aquatic plant life consumed by individuals in the United States, a low likelihood and consequence was assumed for the aquatic plants-to-man link. Large quantities of both fresh and salt water animals (primarily fish and shellfish) are consumed annually by individuals in United States. Consumption of this type of food product is normally considered in a performance assessment [Helton and Kaestner, 1981; NRC, 1981c]. Both sport and commercial fishing activities provide opportunity for contaminated aquatic animals to be introduced into the diet. The transport of radionuclides along this link is dependent upon a number of site-specific factors such as the types and quantities of aquatic animal present and the proximity of the fishing or harvesting grounds to the disposal facility. To allow the potential for human exposure by this potentially significant means, a high likelihood and significance was assigned to the aquatic animals-to-man link. It should be noted, however, that the available data normally incorporates the effects of transport along the aquatic plants-to-aquatic animals link into the overall water to fish transfer data.

2.5 Three-Media Pathways

The pathways constructed using three intermediate media are shown in Table 2-3. A total of 133 pathways were constructed using all nonrepeated three intermediate media combinations of the interactions identified in Figure 2-2. The likelihood and significance levels discussed and assigned to the source-to-medium, medium-to-medium, and medium-to-man links in Sections 2.3 and 2.4 were carried over and directly applied to the three-media pathways. The majority of the three-media pathways may be eliminated from further consideration by virtue of the existence of a low significance link and/or the existence of a higher significance parallel pathway. The "minimum value" accumulation of significance results in a low significance for the pathway if any low significance links are present in the pathway. Also, for a large number of the three-media pathways, a shorter analogous pathway exists that accounts for the mechanism of exposure to man. In general, shorter pathways result in less dilution and require shorter transport time. This implies that transport along these shorter pathways will lead to quicker exposures to higher concentrations of radionuclides and result in higher significances. Only the three-media pathways that have the potential for significant doses to man are discussed in this section.

The three-media pathways with a potential for high significance are listed in the summary Table 2-4. All of these pathways are associated with the transport and propagation of radionuclides through the food chain. The pathways in Table 2-4 were constructed by adding a food chain link to the high significance two-media pathways. The potential for bioaccumulation resulting from long-term exposure in the food chain makes these pathways important. The ground water-to-surface water-to-aquatic animals pathway is included because no parallel pathway exists to account for human exposure from aquatic animals for the undisturbed performance of a disposal facility. In effect, the significance of transport along the ground water-to-surface water link was increased to a high value if no disruptive event was assumed to occur.

Table 2-4 presents two links existing in the three-media pathways that have not yet been discussed. The first of these links involves transfer of radionuclides from land plants-to-land animals. Radionuclides may be introduced into both wild and domestic animals by ingestion of contaminated plants. Grazing and foraging animals are normally the first to become contaminated. These radionuclides then move up the food chain to man. The transfer of radionuclides to animals by consumption of contaminated wild and cultivated plants is normally considered in performance assessment [Helton and Kaestner, 1981; NRC, 1981c]. To allow transfer of radionuclides by this mechanism, a high likelihood was assigned to the land plants-to-land animals link. The amount of radionuclides transferred across this link depends upon both the plant concentration and length of animal exposure. Note that the bioaccumulation can potentially compound across the plants-to-animals links. Since the compounding reconcentration effect from long-term exposure can result in significant quantities of radionuclides existing in animals, a high significance was assigned to the land plants-to-land animals link.

Transfer of radionuclides along the aquatic plants-to-aquatic animals link is analogous to the transfer in the terrestrial food chain. While the simplest aquatic life would normally consume contaminated plant matter, radionuclides will propagate up the aquatic food chain. As with the terrestrial food chain link, a high likelihood and significance were assigned to this link.

2.6 Four-Media Pathways

For completeness, four pathways constructed using four intermediate media should be included for consideration as important radionuclide transport pathways. These pathways are listed in Table 2-5. These pathways were constructed by inserting a plants-to-animals link in the high significance three-media pathways. As discussed in Section 2.5, these pathways become important as a result of the propagation through and accumulation of radionuclides in the food chain. Again for these pathways, the ground water-to-surface water link is only important when the undisturbed performance of the disposal facility is considered.

2.7 Important Generic Pathways

The likelihood and significance assigned to the source-to-medium, medium-to-medium, and medium-to-man links are summarized, respectively, in Tables 2-6, 2-7, and 2-8. By propagating these likelihood and significance levels through the potential migration and exposure pathways presented in Tables 2-1, 2-2, and 2-3, the important pathways for radionuclide transport from a generic low-level waste disposal facility may be identified. The sets of parallel pathways identified by this procedure as being potentially important are presented in Tables 2-9 and 2-10. The order of the pathways listed in Tables 2-9 and 2-10 does not imply an order of importance.

Table 2-9 presents the potentially important pathways associated with the undisturbed performance of the disposal facility. The pathways in this table represent the direct exposure of man from contaminated ground water and the propagation of radionuclides from ground water through the food chain and to man. These pathways become important when it is assumed that (1) the containment structure and soil cover remain intact and perform as designed to provide adequate shielding and minimize infiltration; (2) large amounts of gaseous waste and/or organic waste which result in radionuclide-tagged decomposition gases are not disposed of at the facility; and (3) the disposal facility was designed with a minimum of 3 m of soil cover and possibly includes a concrete containment structure so that plant and animal intrusion is unlikely. All of the pathways presented in Table 2-9 are driven by infiltration into the containment structure with ground water being the medium into which radionuclides are initially released. The infiltration rate is dependent upon a number of site-specific factors including: hydraulic properties; evapotranspiration rates; and the amounts of precipitation and runoff. In this generic study, it was assumed that some infiltration will occur and, thus, transport along all of these pathways is likely.

The pathways presented in Table 2-10 may be important after the occurrence of an event that disrupts the integrity of the containment structure and/or exposes waste at the surface. Events that disrupt the integrity of the containment structure and/or soil cover were placed into two categories: naturally occurring events and events resulting from the activities of an intruder. Naturally occurring events include such things as wind and water erosion, earthquakes and landslides, and containment structure subsidence or collapse. The likelihood of occurrence of these events is a site-specific consideration and difficult to predict, but design and engineering criteria developed to minimize their likelihood of occurrence may be easily incorporated into the design of a low-level waste disposal facility. Also, the siting criteria for low-level waste disposal facilities specifies selecting a location where the likelihood of occurrence of natural events which may adversely affect the ability of the facility to contain waste is low. Thus, a low likelihood is associated with the pathways listed in Table 2-10 when radionuclides are assumed to be released by a naturally occurring disruptive event.

Intruder induced disruptive events include such activities as construction, drilling, and resource exploration and/or exploitation at the disposal facility. These activities can potentially compromise the integrity of the containment structure and its soil cover and/or result in exhumation of the waste. Agricultural activities at the site can enhance mixing of the waste in the environment and promote radionuclide transport in the food chain. The activities of a future intruder are very difficult to predict, but siting criteria for low-level waste disposal facilities are designed to locate the facility in a region where the likelihood of future disruptive activities is minimized. Despite this, certain types of intruder activity such as construction and farming are normally assumed to occur as a part of a performance assessment. Due to this consideration, a high likelihood is associated with the pathways listed in Table 2-10 when radionuclides are assumed to be released by an intruder induced disruptive event.

The ground water pathways, with the exception of those associated with a ground water-to-surface water link, remain important for the disturbed performance of a low-level waste disposal facility. Events which disrupt the integrity of the containment structure and/or soil cover can be expected to increase infiltration and potentially increase the consequences that result from transport along these pathways. The pathways involving a ground water-to-surface water link become less important because a more direct means for the introduction of radionuclides into surface water exists. Once the containment structure is disrupted and waste is available at or near the surface, opportunities for the introduction of radionuclides into the atmosphere and surface water exist. The magnitude and duration of the contamination in these media is highly dependent on prevailing climatic conditions such as the amount of precipitation and direction and speed of wind. The radionuclides introduced into the atmosphere and surface water are then propagated through the food chain to man in a manner similar to that of the ground water driven pathways. The relative importance of pathways associated with contaminated soil is dependent upon the location of the individuals receiving the dose. When the receptor is assumed to be an onsite intruder, higher doses are received from direct gamma radiation resulting from proximity to and/or contact with the waste and ingestion of plants and crops grown in a soil and waste mixture. If the receptor is located offsite, the direct source-to-man and source-to-soil links do not exist. In this case, the radionuclides must first be transported to the offsite location by another medium such as air or water and then deposited in the soil. Once offsite soil is contaminated, human exposure may occur as a result of contact with and/or proximity to soil and ingestion of food products grown in the soil.

Table 2-1
One-Medium Pathways

source-------air-------man
source-------soil------man
source--ground water---man
source---land plants---man
source---land animals--man
source--surface water--man

Table 2-2
Two-Media Pathways

source------air------------soil-----man
source------air---------land plants---man
source------air---------land animals--man
source------air--------surface water--man
source------soil-----------air------man
source------soil-------ground water---man
source------soil--------land plants---man
source------soil--------land animals--man
source------soil-------surface water--man
source---ground water--------air------man
source---ground water--------soil-----man
source---ground water----land plants---man
source---ground water----land animals--man
source---ground water---surface water--man
source---land plants---------air------man
source---land plants---------soil-----man
source---land plants-----land animals--man
source---land plants----surface water--man
source---land plants---aquatic animals-man
source---land animals--------air------man
source---land animals--------soil-----man
source---land animals----land plants---man
source---land animals---surface water--man
source---land animals--aquatic animals-man
source--surface water--------air------man
source--surface water--------soil------man
source--surface water------sediment----man
source--surface water----ground water--man
source--surface water----land plants---man
source--surface water----land animals--man
source--surface water---aquatic plants-man
source--surface water--aquatic animals-man

Table 2-3
Three-Media Pathways

source	air	soil	ground water	man
source	air	soil	land plants	man
source	air	soil	land animals	man
source	air	soil	surface water	man
source	air	land plants	soil	man
source	air	land plants	land animals	man
source	air	land plants	surface water	man
source	air	land plants	aquatic animals	man
source	air	land animals	soil	man
source	air	land animals	land plants	man
source	air	land animals	surface water	man
source	air	land animals	aquatic animals	man
source	air	surface water	soil	man
source	air	surface water	sediment	man
source	air	surface water	ground water	man
source	air	surface water	land plants	man
source	air	surface water	land animals	man
source	air	surface water	aquatic plants	man
source	air	surface water	aquatic animals	man
source	soil	air	land plants	man
source	soil	air	land animals	man
source	soil	air	surface water	man
source	soil	ground water	air	man
source	soil	ground water	land plants	man
source	soil	ground water	land animals	man
source	soil	ground water	surface water	man
source	soil	land plants	air	man
source	soil	land plants	land animals	man
source	soil	land plants	surface water	man
source	soil	land plants	aquatic animals	man
source	soil	land animals	air	man
source	soil	land animals	land plants	man
source	soil	land animals	surface water	man
source	soil	land animals	aquatic animals	man
source	soil	surface water	air	man
source	soil	surface water	sediment	man
source	soil	surface water	ground water	man
source	soil	surface water	land plants	man
source	soil	surface water	land animals	man
source	soil	surface water	aquatic plants	man
source	soil	surface water	aquatic animals	man
source	ground water	air	soil	man
source	ground water	air	land plants	man
source	ground water	air	land animals	man
source	ground water	air	surface water	man
source	ground water	soil	air	man
source	ground water	soil	land plants	man
source	ground water	soil	land animals	man
source	ground water	soil	surface water	man

Table 2-3 (Continued)

source---ground water----land plants---------air-------man
source---ground water----land plants---------soil------man
source---ground water----land plants-----land animals--man
source---ground water----land plants----surface water--man
source---ground water----land plants---aquatic animals-man
source---ground water----land animals--------air-------man
source---ground water----land animals--------soil------man
source---ground water----land animals----land plants---man
source---ground water----land animals---surface water--man
source---ground water----land animals--aquatic animals-man
source---ground water---surface water--------air-------man
source---ground water---surface water--------soil------man
source---ground water---surface water------sediment----man
source---ground water---surface water----land plants---man
source---ground water---surface water----land animals--man
source---ground water---surface water---aquatic plants-man
source---ground water---surface water--aquatic animals-man
source---land plants---------air-------------soil------man
source---land plants---------air---------land animals--man
source---land plants---------air--------surface water--man
source---land plants---------soil------------air-------man
source---land plants---------soil--------ground water--man
source---land plants---------soil--------land animals--man
source---land plants---------soil-------surface water--man
source---land plants-----land animals--------air-------man
source---land plants-----land animals--------soil------man
source---land plants-----land animals---surface water--man
source---land plants-----land animals--aquatic animals-man
source---land plants----surface water--------air-------man
source---land plants----surface water--------soil------man
source---land plants----surface water------sediment----man
source---land plants----surface water----ground water--man
source---land plants----surface water----land animals--man
source---land plants----surface water---aquatic plants-man
source---land plants----surface water--aquatic animals-man
source---land plants---aquatic animals-----sediment----man
source---land plants---aquatic animals---land animals--man
source---land plants---aquatic animals--surface water--man
source---land animals--------air-------------soil------man
source---land animals--------air---------land plants---man
source---land animals--------air--------surface water--man
source---land animals--------soil------------air-------man
source---land animals--------soil--------ground water--man
source---land animals--------soil--------land plants---man
source---land animals--------soil-------surface water--man
source---land animals----land plants---------air-------man
source-- land animals----land plants---------soil------man
source---land animals----land plants----surface water--man
source---land animals----land plants---aquatic animals-man
source---land animals---surface water--------air-------man

Table 2-3 (Continued)

```
source---land animals---surface water--------soil------man
source---land animals---surface water------sediment----man
source---land animals---surface water----ground water--man
source---land animals---surface water----land plants---man
source---land animals---surface water---aquatic plants-man
source---land animals---surface water--aquatic animals-man
source---land animals--aquatic animals-----sediment----man
source---land animals--aquatic animals--surface water--man
source--surface water--------air------------soil------man
source--surface water--------air---------land plants---man
source--surface water--------air---------land animals--man
source--surface water--------soil------------air-------man
source--surface water--------soil--------ground water--man
source--surface water--------soil--------land plants---man
source--surface water--------soil--------land animals--man
source--surface water------sediment-----aquatic plants-man
source--surface water------sediment----aquatic animals-man
source--surface water----ground water--------air-------man
source--surface water----ground water--------soil------man
source--surface water----ground water----land plants---man
source--surface water----ground water----land animals--man
source--surface water----land plants---------air-------man
source--surface water----land plants---------soil------man
source--surface water----land plants-----land animals--man
source--surface water----land plants---aquatic animals-man
source--surface water----land animals--------air-------man
source--surface water----land animals--------soil------man
source--surface water----land animals----land plants---man
source--surface water----land animals--aquatic animals-man
source--surface water---aquatic plants-----sediment----man
source--surface water---aquatic plants---land animals--man
source--surface water---aquatic plants-aquatic animals-man
source--surface water--aquatic animals-----sediment----man
source--surface water--aquatic animals---land animals--man
```

Table 2-4
Three-Media Pathways with the Potential
for Significant Human Exposure

source------air	soil	land plants	man
source------air	land plants	land animals	man
source------soil	land plants	land animals	man
source---ground water	soil	land plants	man
source---ground water	land plants	land animals	man
source---ground water	surface water	aquatic animals	man
source--surface water	soil	land plants	man
source--surface water	land plants	land animals	man
source--surface water	aquatic plants	aquatic animals	man

Table 2-5
Four-Media Pathways with the Potential
for Significant Human Exposure

source-----air	soil	land plants	land animals	man
source--ground water	soil	land plants	land animals	man
source--ground water	surface water	aquatic plants	aquatic animals	man
source-surface water	soil	land plants	land animals	man

Table 2-6
Likelihood and Significance of
Source-to-Media Links

	Undisturbed	Naturally Disturbed	Intruder Disturbed
source------man (a)	low/low (b)	low/high	high/high
source------air	high/low	low/high	high/high
source------soil (a)	low/low	low/high	high/high
source---ground water	high/high	high/high	high/high
source---land plants	low/low	low/low	high/low
source--land animals	low/low	low/low	high/low
source--surface water	low/low	low/high	high/high

notes: (a) These links are only valid for onsite receptors.
(b) This notation denotes likelihood/significance.

Table 2-7
Likelihood and Significance of Media-to-Media Links

	Likelihood	Consequence
air-----------soil	high	high (a)
air------land plants	high	high
air------land animals	high	low
air------surface water	high	low
soil-----------air	high	low
soil------ground water	high	low
soil------land plants	high	high
soil------land animals	high	low
soil------surface water	high	low
ground water--------air	high	low
ground water--------soil	high	high
ground water----land plants	high	high
ground water----land animals	high	high
ground water---surface water	high	low
land plants-----land animals	high	high
surface water--------air	high	low
surface water--------soil	high	high
surface water------sediment	high	high
surface water----ground water	high	low
surface water----land plants	high	high
surface water----land animals	high	high
surface water---aquatic plants	high	high
surface water--aquatic animals	high	high
aquatic plants-aquatic animals	high	high

note: (a) A low ranking should be used for an onsite receptor.

Table 2-8
Likelihood and Significance of Media-to-Man Links

	Likelihood	Significance
air--------man	high (a)	high
soil-------man	high	high (b)
sediment-----man	high	low
ground water---man	high	high
land plant-----man	high	high
land animals---man	high	high
surface water---man	high	high
aquatic plants--man	low	low
aquatic animals--man	high	high

note: (a) Use low ranking for undisturbed facility and offsite receptor.
(b) Use low ranking for disturbed facility and onsite receptor.

Table 2-9
Important Generic Pathways for the Undisturbed Performance of Low-Level Waste Disposal Facilities

source-ground water-man
source-ground water------soil-----man
source-ground water--land plants--man
source-ground water--land animals-man
source-ground water-surface water-man
source-ground water------soil------land plants---man
source-ground water--land plants----land animals--man
source-ground water-surface water-aquatic animals-man
source-ground water------soil------land plants-----land animals--man
source-ground water-surface water--aquatic plants-aquatic animals-man

Table 2-10
Important Generic Pathways for the Disturbed Performance of Low-Level Waste Disposal Facilities

source------man (a)
source------air------man
source--ground water--man
source-surface water-man
source------air-----------soil------man (b)
source------air-------land plants---man
source------soil------land plants---man (a)
source--ground water--------soil------man (b)
source--ground water----land plants---man
source--ground water----land animals--man
source-surface water------soil------man (b)
source-surface water---land plants---man
source-surface water---land animals--man
source-surface water-aquatic animals-man
source------air-----------soil--------land plants---man (b)
source------air-------land plants-----land animals--man
source------soil------land plants-----land animals--man (a)
source--ground water--------soil--------land plants---man (b)
source--ground water----land plants-----land animals--man
source-surface water------soil--------land plants---man (b)
source-surface water---land plants-----land animals--man
source-surface water--aquatic plants-aquatic animals-man
source------air-------soil-----land plants---land animals--man (b)
source--ground water---soil-----land plants---land animals--man (b)
source-surface water---soil-----land plants---land animals--man (b)

notes: (a) These pathways are important only for onsite receptors.
(b) These pathways are important only for offsite receptors.

3.0 REGIONAL CONSIDERATIONS

A large number of regional conditions can potentially affect the significance of radionuclide transport along the various migration and exposure pathways. These regional considerations include location of potential receptors, existence of certain physical features, values of physical properties and parameters, prevailing climatic conditions, and the likelihood of certain disruptive events. The introduction of radionuclides into surface water and ground water is driven by precipitation. Amounts of annual rainfall greatly affect the magnitude and duration of contamination in these media. The existence of nearby ponds, lakes, and streams can greatly affect how surface water contamination is accumulated and propagated through the food chain. Parameters such as evapotranspiration rate, soil water content and hydraulic conductivity, and depth to the water table affect when and if radionuclides reach the saturated zone for further transport to man and the food chain. Transport of radionuclides along the atmospheric pathway is dependent upon wind speed and associated suspension rate, wind direction, topology and existence of certain surface features, and wet and dry deposition rates.

To include consideration of these regional features in this study, two generic sets of regional site conditions were defined: an arid site and a humid site. Descriptions of reference sites in these regions have been previously developed [Murphy and Holter, 1980; McKenzie et al., 1982, 1983] and were used to develop the descriptions presented here. After a brief overview of the regional conditions considered, the results of an evaluation of the pathways previously identified as potentially important using this additional information is presented. The result is a summary of the potentially important migration and exposure pathways for each of the two generic regions. At the end of this section, a brief discussion of potential effects of temperature range on the assessment of potential migration and exposure pathways is presented.

3.1 Arid Site

The arid western site is assumed to have a desert-like climate with low annual rainfall and high evapotranspiration rates. The precipitation rate is on the order of 20 cm/yr or less with most precipitation occurring in late fall and early winter. Evaporation and evapotranspiration result in the return of virtually all of the annual precipitation to the atmosphere. Average wind speeds are in range of 2-5 m/s with frequent peak gusts exceeding 20 m/s. The surface soil is primarily composed of sand and gravel with some intermixed clay and silt. The soil is assumed to have a moderate to high permeability and a relatively low sorptive capacity. The distance to bedrock is in excess of 100 m and the water table is located on the order of 50 m below the land surface. No perennial surface water exists in the vicinity of the disposal facility. The nearest surface water of any consequence is assumed to be at a distance of 15 km or more. Due to lack of water, limited amounts and types of flora and fauna exist in the region. Shrubs and grasses are assumed to be the primary forms of vegetation at the site. Some larger animals such as deer do exist in the vicinity of the site but the animal community is assumed to be dominated by small to medium-sized mammals. The small mammals and some invertebrates in the animal community construct burrows. The animal burrowing and plant root depth is assumed to be limited to no more than the first 3 m below the surface.

The potentially important pathways for transport of radionuclides at the reference arid site for undisturbed and disturbed facility performance are shown, respectively, in Tables 3-11 and 3-12. The pathways shown in these tables differ from those previously identified as important in that the ground water-to-surface water, surface water-to-plants, and surface water-to-animals links are insignificant. These links become less important at the arid western site because no surface water was assumed to exist in the vicinity of the disposal facility. Recharge and discharge of underlying aquifers are unlikely due to the assumed depth of the water table. Without perennial surface water, aquatic life cannot exist. The limited amounts of rainfall and lack of significant perennial surface water minimizes opportunities for radionuclides to be transferred to land plants and animals. The surface water-to-soil link was retained for the disturbed performance of the disposal facility because, even with limited precipitation, some runoff will occur and the high evaporation rates will likely result in deposition in soil of radionuclides mobilized by this runoff.

The pathways associated with infiltration into the containment structure are retained but the likelihood and significance of transport along these ground water driven pathways is greatly reduced for an arid site. The combination of the low precipitation with the high evaporation and evapotranspiration rates will result in very small (if any) amounts of infiltration into the containment structure. The majority of infiltrating water is likely to be retained in the near surface. This, when considered in conjunction with depth to the water table, should result in minimal amounts of radionuclides reaching the saturated zone for further transport to man and the food chain. The likelihood of radionuclide transport along the ground water driven pathways is low, especially for the undisturbed performance of the disposal facility. The likelihood of ground water transport at an arid site is expected to be roughly equivalent to that of many of the naturally occurring disruptive events. This estimation of likelihood is supported by consideration of the high perennial wind speeds, which would promote loss of surface soil and increase the likelihood of significant surface erosion.

The pathways associated with atmospheric transport will be dominant for arid western sites. The amount of water available to transport radionuclides is very limited, thus air becomes the primary medium for transport to man and the food chain. The relatively high winds support high suspension rates once waste is exposed at or near the surface. The existence of significant perennial winds indicates the potential for the long-term and wide-spread transport of radionuclides. Certain activities of man, such as agricultural irrigation, will increase the likelihood of transport along water driven pathways, but atmospheric transport will remain important in these cases.

3.2 Humid Site

The reference humid site is assumed to have a climate that is representative of much of the middle to eastern United States. A wide annual temperature variation exists and large amounts of precipitation occur at the site. The summers are generally hot and humid and the winters are cold and have a significant number of days with temperatures below freezing. Precipitation rates are on the order of 100 cm/yr or more with the majority of the rainfall occurring in the late spring and summer months. Significant snowfall and snowpack normally occur during the winter months. Peak winds generally occur in the spring and average approximately 5km/hr [McKenzie et al., 1983]. The surface soil is composed primarily of clays with some intermixed sand and silt. The soil is expected to have a low permeability and relatively high sorptive capacity. Sand lenses that can have significantly higher permeabilities are potentially present in the vicinity of the site. The distance to bedrock is assumed to be 20-30 m. The water table is shallow, on the order of 10 m below the surface. Due to the high precipitation, a significant infiltration rate is expected and the underlying aquifer is assumed to be recharged through the site. Significant amounts of surface water are assumed to exist in the immediate vicinity of the site. These range from small streams found within 1 km of the site to larger lakes and a river located within 10 km. It is assumed that the larger surface water bodies are widely used by man for recreational activities such as boating, swimming, and fishing. The majority of the land in the immediate vicinity of the facility is used by man for agricultural or recreational activities. The abundant supply of water in the area supports a large quantity and variety of biota. Plant life ranges from grass, shrubs, and trees to cultivated crops. The animal life is dominated by small mammals and domestic animals. Small burrowing animals exist at the site, but as in the arid site biotic activity is limited to the first 3 m of the surface soil.

The potentially important migration and exposure pathways for the humid eastern reference site for undisturbed and disturbed facility performance are given, respectively, in Tables 3-13 and 3-14. The primary differences in the sets of pathways presented in these tables result from the abundance of water at the eastern site. Irrigation is generally unlikely at this site due to the assumed high annual rainfall. Thus, direct contamination of soil and land plants from ground water is unlikely and these links are broken. While the proximity of the water table to the surface introduces the possibility that capillary action could bring radionuclides to the root zone and contaminate soil and land plants, a sufficient depth to the water table exists at the reference site to make this a low likelihood event. The ground water-to-man and ground water-to-land animals links are retained because, even with abundant surface water, a high likelihood exists that man and domestic animals will receive drinking water from wells located in a contaminated aquifer.

The existence of significant amounts of surface water in the immediate vicinity of the site increases the importance of associated pathways. This is especially true of the undisturbed performance of the disposal facility, where surface water contaminated by ground water discharge is the primary means for radionuclides to enter both aquatic and terrestrial food chains. Radionuclides may enter land animals as a result of ingestion of the perennial surface waters in the immediate vicinity of the disposal facility. Flood and runoff provide mechanisms for the contamination of soil and land plants. The ground water-to- surface water link becomes less important for the disturbed performance of the facility because the more direct means of runoff exists for contamination of surface water.

Water driven pathways will dominate human exposure at humid eastern sites for both the undisturbed and disturbed performance of the disposal facility. The relatively low wind velocities and humid conditions will result in low suspension rates, limiting significances of the atmospheric transport pathways. The high precipitation anticipated at these sites results in high infiltration and runoff rates which promote migration of radionuclides along both the ground water and surface water pathways. The existence of large amounts of perennial surface water increases the likelihood and significance of human exposures from the aquatic food chain. Certain activities of man, such as agriculture, can be expected to enhance the processes that control transport of radionuclides in the water pathways and further increase their significance.

3.3 Temperature Effects

The temperature ranges existing at a site are highly dependent on regional location. The range of the annual temperatures can affect both the likelihood of occurrence of certain natural events and the types and quantities of fauna and flora present at the disposal facility. Identification and quantification of the effects of the various plants and animals present is a site specific activity and will not be discussed further here.

The temperature effects associated with the likelihood of occurrence of natural disruptive events at a site are primarily a result of the freeze-thaw cycle. If sufficient quantities of moisture are present in the near surface soils of the disposal facility, freeze-thaw cycling can increase the likelihood of disruption of the containment structure and soil cover. Events such as frost heave can lead to increased permeability and thus infiltration in the immediate vicinity of the disposal structure. Freeze and thaw cycling can also increase the rate of degradation of concrete and other materials used in construction of the containment structure. The existence of a snowpack with an associated slow melt could also increase infiltration into the containment structure. The effects of these disruptive events are expected to primarily impact water driven pathways through potentially increased likelihood of occurrence and significance. Since these increased significances are a result of the freeze and thaw cycle, they can be expected to be most pronounced at cold, humid sites.

Table 3-1
Important Generic Pathways for the Undisturbed Performance of an Arid Low-Level Waste Site

source-ground water--man
source-ground water-----soil-----man
source-ground water-land plants--man
source-ground water-land animals-man
source-ground water-----soil-----land plants--man
source-ground water-land plants--land animals-man
source-ground water-----soil-----land plants--land animals-man

Table 3-2
Important Generic Pathways for the Disturbed Performance of an Arid Low-Level Waste Site

source-man (a)
source------air-------man
source--ground water--man
source------air----------soil-----man (b)
source------air------land plants--man
source------soil-----land plants--man (a)
source--ground water-----soil-----man (b)
source--ground water-land plants--man
source--ground water-land animals-man
source-surface water-----soil-----man (b)
source------air----------soil-----land plants--man (b)
source------air------land plants--land animals-man
source------soil-----land plants--land animals-man (a)
source--ground water-----soil-----land plants--man (b)
source--ground water-land plants--land animals-man
source-surface water-----soil-----land plants--man (b)
source------air----------soil-----land plants--land animals-man (b)
source--ground water-----soil-----land plants--land animals-man (b)
source-surface water-----soil-----land plants--land animals-man (b)

notes: (a) These pathways are important only for onsite receptors.
(b) These pathways are important only for offsite receptors.

Table 3-3

Important Generic Pathways for the Undisturbed Performance of a Humid Low-Level Waste Site

source-ground water--man
source-ground water--land animals--man
source-ground water-surface water--man
source-ground water-surface water------soil------man
source-ground water-surface water---land animals--man
source-ground water-surface water-aquatic animals-man
source-ground water-surface water-------soil--------land plants----man
source-ground water-surface water--aquatic plants--aquatic animals-man
source-ground water-surface water--soil--land plants--land animals-man

Table 3-4

Important Generic Pathways for the Disturbed Performance of a Humid Low-Level Waste Site

source-man (a)
source------air-------man
source--ground water--man
source-surface water--man
source------air------------soil------man (b)
source------air--------land plants---man
source------soil-------land plants---man (a)
source--ground water---land animals--man
source-surface water-------soil------man (b)
source-surface water---land plants---man
source-surface water---land animals--man
source-surface water-aquatic animals-man
source------air------------soil--------land plants---man (b)
source------air--------land plants-----land animals--man
source------soil-------land plants-----land animals--man (a)
source-surface water-------soil--------land plants---man (b)
source-surface water---land plants-----land animals--man
source-surface water--aquatic plants-aquatic animals-man
source-----air----------soil--------land plants---land animals--man (b)
source-surface water----soil--------land plants---land animals--man (b)

notes: (a) These pathways are important only for onsite receptors.
(b) These pathways are important only for offsite receptors.

4.0 CONCLUSIONS

An assessment of the relative significance of pathways for the migration and exposure of radionuclides from a low-level waste disposal facility to man has been performed using generic criteria. A pathway assessment of this type is a necessary part of performance assessment because it insures that, of the large number of potential migration and exposure pathways that exist, all pathways with a high likelihood of resulting in doses to humans are analyzed and their impacts evaluated. Both the likelihood and significance of transport of radionuclides along a pathway must be addressed in considering the results of the pathway assessment.

None of the lists of important migration and exposure pathways included in the tables included in this document are meant to supply a complete set of pathways to be analyzed during the performance assessment of any current or future disposal facility. Pathway identification and assessment is a site- specific activity and the lists included in this document are based entirely on a set of generic considerations. When actual site information is used, a pathway identified here as important may no longer be important. The existence or absence of certain features at the site may allow some additional links and/or pathways to be eliminated. Consideration of site-specific data may also change the ranking of pathways. Pathways assigned a lower priority in this generic study may emerge as more important.

A procedure to assist an analyst in the site-specific identification of important migration and exposure pathways for performance assessment has been presented. This procedure is based upon identification of events and circumstances that lead to transfer of radionuclides along the links in a pathway. Using site-specific data related to these events and circumstances, the analyst can both determine the likelihood of transfer of radionuclides along the link and assess the relative impact of the transfer in terms of potential dose to man. Once the likelihood and significance of transfer of radionuclides along all of the links in a pathway have been determined, the likelihood and significance of transfer along the pathway are evaluated by tracking and accumulating the values of the links.

The ranking procedure was applied to the potential migration and exposure pathways of radionuclides identified in Shipers [1989] to develop a generic set of critical pathways for low-level waste disposal facilities. The critical pathways are divided into two groups based on the conditions that lead to initial release of radionuclides from the containment facility. The critical pathways associated with the undisturbed performance of the disposal facility are driven primarily by infiltration of precipitation. After radionuclides are introduced into ground water by this process, they are transported to man both directly and indirectly via contamination of the food chain. When an event occurs that disrupts the integrity of the containment structure or exposes waste at the surface, pathways associated with the direct introduction of radionuclides into the atmosphere and surface water also become important. As with the ground water pathways, once radionuclides are introduced into the atmosphere and surface water, they may be transported to man both directly and indirectly via food chain contamination. Events which may result in the disruption of the containment structure and/or soil cover are divided into two categories: naturally occurring events and events induced by the activities of an intruder. Naturally occurring disruptive events are assumed to have a low likelihood of occurrence. Disruptive events that are associated with the activities of man are assumed in this analysis to be likely.

Regional and climatic considerations were also applied to the two groups of critical generic pathways. At arid sites, the ground water pathways are generally less dominant and the likelihood of transport along these pathways can be considered to be roughly equivalent to that associated with naturally occurring disruptive events. When low infiltration rates are considered in conjunction with high average wind velocites, pathways driven by atmospheric transport are expected to be dominant at arid sites. At humid sites, the transport of radionuclides to man is dominated by surface water and ground water pathways. Infiltration resulting in the transport of radionuclides into the ground water for the undisturbed performance of a disposal facility is the most significant pathway at humid sites.

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An assessment of the relative significance of pathways for the migration and exposure of radionuclides from a low-level waste disposal facility to man is described in this document. Initiating events and circumstances associated with the undisturbed, naturally disturbed, and artificially disturbed performance of low-level waste facilities are considered during the ranking procedure of potential migration and exposure pathways. In this ranking procedure, relative measures are assigned to the likelihood of occurrence of the events and circumstances leading to migration and exposure of radionuclides, and to the potential level of significance in terms of dose to man. Based on this ranking procedure, a set of generic important pathways for low-level waste disposal facilities are developed and presented.

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