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Performance Evaluation of the Technical Capabilities of DOE Sites for Disposal of Mixed Low-Level Waste

Volume 1: Executive Summary

Prepared by the Department of Energy (DOE)
Office of Waste Management
Federal Facility Compliance Act
Disposal Workgroup

March 1996
Sandia National Laboratories
Albuquerque, New Mexico

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ABSTRACT

A team of analysts designed and conducted a performance evaluation to estimate the technical capabilities of fifteen Department of Energy sites for disposal of mixed low-level waste (i.e., waste that contains both low-level radioactive materials and hazardous constituents). Volume 1 summarizes the process for selecting the fifteen sites, the methodology used in the evaluation, and the conclusions derived from the evaluation. Volume 2 provides details about the site-selection process, the performance-evaluation methodology, and the overall results of the analysis. Volume 3 contains detailed evaluations of the fifteen sites and discussions of the results for each site.

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PREFACE

This report documents the performance evaluation of facilities at various Department of Energy (DOE) sites relative to their capabilities for the disposal of mixed low-level waste (MLLW). The principal goal in developing the performance evaluation (PE) was to estimate the limiting concentrations of radionuclides in residuals resulting from treatment of MLLW for disposal at these sites. The report consists of three volumes:

> Volume 1 is an executive summary both of the PE methodology and of the results obtained from the PEs. While this volume briefly reviews the scope and method of analyses, its main objective is to emphasize the important insights and conclusions derived from the conduct of the PEs.
>
> Volume 2 first describes the screening process used to determine the sites to be considered in the PEs. This volume then provides the technical details of the methodology for conducting the performance evaluations. It also provides a comparison and analysis of the overall results for all sites that were evaluated.
>
> Volume 3 presents the results of the PEs for the 15 sites considered in the process. This presentation includes a discussion of the conceptual models and data used in the PE for each site.

The PE is not a substitute for the detailed analyses provided by performance assessments required by DOE Order 5820.2A; rather, it is a means for the DOE and the States to begin evaluating options for disposal of MLLW treatment residuals. The ultimate identification of sites that may host MLLW disposal activities will follow state and federal regulations for siting and permitting and will include public involvement in the decision-making process. The appropriate site-specific performance or risk assessments and environmental impact analyses in accordance with the National Environmental Policy Act will be required in determining limits on quantities of radionuclides that may be acceptable for disposal at any site.

NOMENCLATURE

ANLE	Argonne National Laboratory—East
$C_{W\text{-}Atm}$	Radionuclide-specific waste concentration for permissible atmospheric releases
CFR	Code of Federal Regulations
CRF	Concentration reduction factor
DOE	Department of Energy
DWG	Disposal Workgroup
EPA	Environmental Protection Agency
FEMP	Fernald Environmental Management Site
FFCAct	Federal Facility Compliance Act
INEL	Idaho National Engineering Laboratory
LANL	Los Alamos National Laboratory
LDR	Land Disposal Restrictions
LLNL	Lawrence Livermore National Laboratory
LLW	Low-level waste
MLLW	Mixed low-level waste
MWIR	Mixed Waste Inventory Report
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
ORR	Oak Ridge Reservation
PE	Performance evaluation
PGDP	Paducah Gaseous Diffusion Plant
PORTS	Portsmouth Gaseous Diffusion Plant
RCRA	Resource Conservation and Recovery Act
RFETS	Rocky Flats Environmental Technology Site
SNL	Sandia National Laboratories
SRS	Savannah River Site
WVDP	West Valley Demonstration Project

EXECUTIVE SUMMARY

The Federal Facility Compliance Act (FFCAct) of 1992 requires the U.S. Department of Energy (DOE) to work with its regulators and with members of the public to establish plans for the treatment of DOE's mixed low-level waste (MLLW). Along with other radioactive and hazardous waste, MLLW has been generated for more than 50 y through DOE activities related to the production of materials for nuclear weapons and research with nuclear materials. The DOE currently generates, stores, or expects to generate (over the next five years) about 650,000 m^3 of MLLW at 41 sites in 20 states. Although the FFCAct does not specifically address disposal of treated MLLW, both DOE and the States recognize that disposal issues are an integral part of treatment discussions. The DOE, in collaboration with the States, has responded to MLLW treatment and disposal issues in two ways:

- The DOE began developing plans (called "site treatment plans") for assessing both the capacity and capabilities for treating mixed waste for each facility at which it stores or generates such wastes. Following a three-phase approach, conceptual site treatment plans for each site were submitted to the appropriate regulatory agencies (the relevant states and the U.S. Environmental Protection Agency) in October 1993; draft site treatment plans were submitted in August 1994; and proposed site treatment plans were submitted in April 1995. Implementation of these plans was formalized through consent orders issued by the appropriate regulatory agencies by October 1995 for most sites.

- The DOE established the FFCAct Disposal Workgroup (DWG) in June 1993 to work with the States in defining and developing a process for evaluating disposal options for treated MLLW. The focus of the DWG process and of discussions on disposal with the States has been to identify, from among the sites currently storing or expected to generate MLLW, those that are suitable for further evaluation in terms of their disposal capabilities.

The performance evaluation (PE) discussed in this report was designed to quantify and compare the potential technical capabilities of 15 DOE sites for MLLW disposal to provide information to decision makers developing plans for the configuration of sites for disposal of DOE MLLW. The principal goal of the PE was to estimate, assuming grouted residuals that result from the treatment of MLLW, permissible concentrations of radionuclides in waste for disposal at each site. These "permissible waste concentrations" were based solely on long-term performance of the disposal facility and surrounding environment and did not take into account any policy or operational waste acceptance criteria that might have been developed for a particular site. To provide a common frame of reference, grout was the waste form evaluated in the PE because the majority of treated and stabilized DOE MLLW is anticipated to have been stabilized by this method, although other waste forms may be used.

The existing levels of contamination that may exist at the 15 sites have not specifically been considered in this analysis. The site analyses did not consider the effects of overlapping plumes from nearby disposal facilities or accidental releases. These considerations will be included in a site-specific performance assessment and are being addressed by DOE in its implementation of the Defense Nuclear Facilities Safety Board Recommendation 94-2. The PE used analyses that are consistent with the approach currently used in many low-level waste (LLW) performance assessments. The objective was to use a set of modeling assumptions of sufficient detail to capture major site-specific characteristics and yet be general enough for consistent application at all sites. Additionally, the analyses were designed to ensure that the sites were analyzed consistently and that all major assumptions were clearly stated.

Details of the background and the results of the evaluations of the capabilities of the DOE sites for disposal of treated MLLW residuals are provided in the three volumes of this report.

1.0 HISTORY OF THE DISPOSAL PROJECT

The DOE established the DWG in June 1993 to work with the States in defining and developing a process for evaluating options for disposal of treated MLLW. As a first step, the DWG combined 5 of the 49 sites with other sites under consideration based on geographic proximity and then screened the remaining sites* (Figure 1) against three exclusionary criteria that were derived from regulatory and DOE sources: the site must have a possible location for disposal that (1) is not located within a 100-y floodplain; (2) is not located within 61 m (200 ft) of an active fault; and (3) has sufficient area to accommodate a 100-m (328-ft) buffer zone. After completion of this initial screening procedure, DOE and the States jointly agreed in March 1994 that 18 sites could be dismissed from further evaluation.

The DOE prepared "site fact sheets" on the remaining 26 sites (see Figure 1) that provided additional site-specific information for identifying their strengths and weaknesses for the purpose of disposal activities based on a list of factors developed by DOE and the States. The DWG used these factors in the site fact sheets to evaluate the sites according to three criteria: technical considerations (e.g., hydrology, earthquake potential, soil stability), potential receptor considerations (e.g., population changes, sensitive environments), and practical considerations (e.g., ownership, mission, MLLW volumes). For each of these criteria, the DWG then grouped the sites into one of three categories in terms of their acceptability for disposal activities: the site posed (1) a major problem; (2) a moderate problem; or (3) a minor problem. Sites with major problems were defined as having features or attributes that make developing and operating a disposal facility extraordinarily difficult. Moderate problems were defined as significant problems that could likely be solved with additional efforts and resources. Sites designated as having minor problems were those having neither major nor moderate problems.

Based on these evaluations, 5 sites were eliminated from further consideration and 4 were assigned a low priority for further consideration during the July 1994 meeting between DOE and the States. Low priority sites will be evaluated further only if no other options can be identified through the disposal evaluation process. Subsequently, one site was combined with another, and an additional site was assigned a low priority for evaluation. One site, WVDP, was evaluated for disposal of on-site radionuclides only.

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* Information compiled since 1993 indicates that the DOE currently generates, stores, or expects to generate (over the next five years) MLLW at 41 sites.

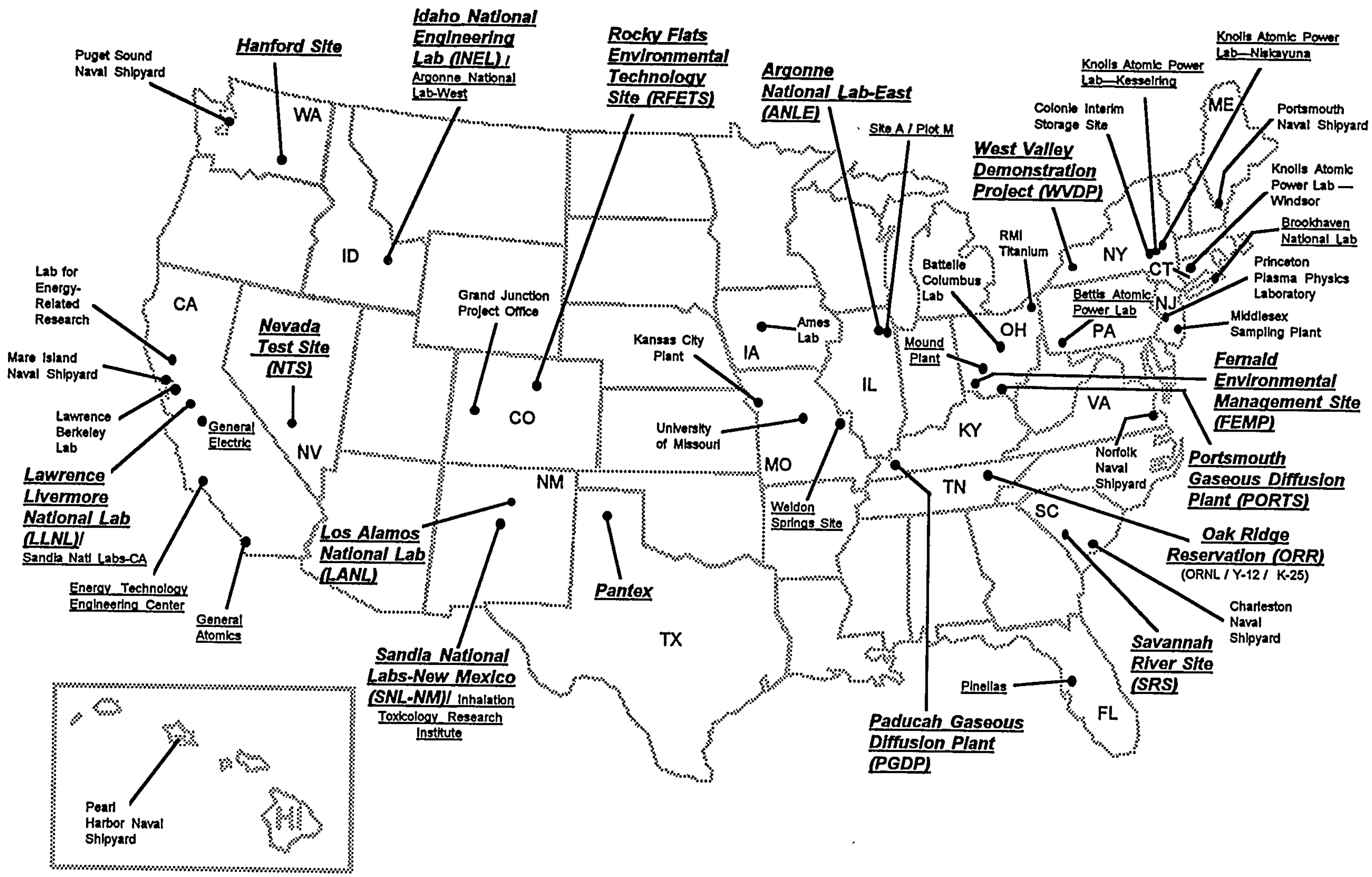


Figure 1. Forty-nine sites originally considered by the DWG in the screening process. The 26 underlined sites are those that remained after the initial screening. The 15 sites in bold italics are those for which performance evaluations were conducted.

As a result of these additional considerations, 15 sites were identified for further review (see Figure 1). For these, the DOE and the States agreed that a more technically detailed performance evaluation should be conducted. This evaluation was expected to increase the existing understanding of the strengths and weaknesses of each site for disposal and to better identify what types of disposal activities could or could not occur at a site.

To initiate the PE process, a workshop sponsored by the DWG was held in August 1994 to allow technical representatives of the 15 sites and interested representatives from the States to become familiar with the process and provide input to the general framework of the PE. One of the outcomes of the workshop was the establishment of the methodology to be used in conducting the performance evaluation. This included assembling two "PE Core Teams", consisting of technical staff members from Sandia National Laboratories and Oak Ridge National Laboratory to collect information from each site, work with site technical staff, and perform the analyses. A steering group and internal and external review panels were also established to ensure quality of the analyses.

2.0 METHODOLOGY OF THE PE

The DWG designed the PE to quantify and compare the potential disposal capabilities of the 15 DOE sites for the disposal of treated MLLW. The principal goal in developing the PE was to estimate, given the assumptions outlined in the PE, the maximum radionuclide concentrations in MLLW (i.e., "maximum waste concentrations") for disposal such that exposures to humans would not exceed the pre-determined performance measures. An additional goal was to complete the analysis with minimal expenditure of resources (e.g., less than $100K per site and one year total effort for all 15 sites). Assumptions pertaining to the size and performance of the generic facilities used in the analysis were used to provide consistency to the analysis of the 15 sites and did not require site-specific waste volumes or inventories.

Although based on simple analyses, the PE was consistent with the approach used in many LLW performance assessments. The objective was to use a set of modeling assumptions that included sufficient detail to capture major site-specific characteristics and yet were general enough for consistent application at all sites. Calculations of releases for three pathways—water, atmospheric, and inadvertent intruder—formed the foundation of the PE.

To ensure technical adequacy, the DWG adopted the strategy that performance evaluations would incorporate

- The input, to the extent practical, of existing knowledge, analyses, and data at each site;
- The application of well-established policies and recommendations on disposal-related issues; and
- The support of extensive and continuous reviews from both internal and external experts.

The PE teams interacted with personnel from each of the sites to assure that they gained maximum benefit from important research, site characterization, modeling, and other analyses that had been or were being performed. In addition to regular exchanges via telephone and correspondence, these interactions included visits by the PE teams to each of the sites. Based on discussions with site personnel who had spent years studying each site, the PE teams incorporated the best documented understanding and technical data into the generic framework of each PE.

The DWG designed the PE analyses to ensure that the sites were analyzed consistently and that all major assumptions were clearly stated. Major assumptions pertaining to three key sets of factors: (1) performance measures and human exposures to releases; (2) the source term and disposal facilities; and (3) transport, are outlined below.

2.1 Performance Measures and Human Exposures to Releases

The DWG made the following determinations and/or assumptions about performance measures and human exposure to radionuclides:

- The performance objectives specified in DOE Order 5820.2A provided the basis for the "performance measures" used in estimating the permissible concentrations of radionuclides in the disposed waste ("permissible waste concentrations"). Following this approach, the permissible waste concentrations were directly linked to the permissible dose limits to individuals for each of the three pathways as specified in the DOE orders, namely:

  - 4 mrem (0.04 mSv) per year from consumption of drinking water resulting from releases to groundwater;
  - 10 mrem (0.1 mSv) per year from all exposure pathways resulting from atmospheric releases; and
  - 100 mrem (1 mSv) per year from all exposure pathways resulting from long-term, chronic exposure of inadvertent intruders after loss of active institutional controls at 100 y after disposal.

  The first performance measure is based on standards for radioactive material in drinking water and generally provides limits on releases to off-site locations that are more restrictive than the limit of 25 mrem (0.25 mSv) per year from all exposure pathways specified in the DOE Order. For the third performance measure, supporting calculations have shown that chronic exposures produced more restrictive waste concentration limits than acute exposures. All of these performance measures exclude doses from radon.

- Doses from radiologically significant decay products were included in the estimation of permissible waste concentrations for the parent radionuclide.

- The period for consideration was 10,000 y from the time the disposal facility was closed. For information purposes, the maximum radionuclide concentrations and arrival times for the water pathway that exceeded the 10,000-y period were calculated and reported. However, these estimates were not considered in determining the most restrictive waste concentrations for any of the three pathways. For inadvertent intrusion by the homesteader scenario, the performance measure was applied at the earliest time that intrusion was assumed to occur with two exceptions. In the assessments for six radionuclides (U-233, U-234, U-235, U-238, Pu-244, and Cm-247), the time of intrusion was assumed to occur at 10,000 y, the end of the performance period. This was done because ingrowth of decay products for these radionuclides yields scenario doses that increase over time and peak beyond the 10,000-y performance period. This approach was considered to be conservative. Changes were also made in the cases of Th-230 and Cm-245, in which the ingrowth of decay products produces a scenario dose that increases over time and peaks within the 10,000-y performance period. Again, to be conservative the times of intrusion for these two radionuclides (Th-230 and Cm-245) were assumed to occur at the time of maximum dose, 9,000 y for Th-230 and 1,000 y for Cm-245.

- Active institutional controls were considered effective for 100 y after disposal; no active or passive institutional controls were considered effective after 100 y, although some credit was taken for the ability of the engineered barriers to preclude inadvertent intrusion beyond 100 y after disposal.

- For the water and atmospheric pathways, the performance boundary (i.e., point of compliance) was 100 m (328 ft) from the edge of the disposal facility. For the inadvertent intruder pathway, the exposure was assumed to occur where an intruder dug or drilled into the disposal facility.

2.2 Source Term and Disposal Facility

The DWG made the following assumptions about mechanisms for release of radionuclides from the disposal facility (i.e., the source term) and the nature of the disposal facility in regard to design and long-term performance:

- The PE was based solely on a radiological assessment for disposal even though the wastes under consideration also contain hazardous components that are subject to Resource Conservation and Recovery Act (RCRA) requirements. The PE analysis assumed that the chemical components of the wastes would be treated to Land Disposal Restrictions (LDRs) according to RCRA's treatment processes and that MLLW disposal facility would comply with all RCRA design criteria.

- Fifty-eight radionuclides were considered in the PE. This list is based on radionuclides identified in DOE's Mixed Waste Inventory Report (MWIR) and 5 performance assessments conducted for LLW disposal facilities at DOE sites. Radionuclides with half-lives less than 5 y were eliminated from consideration as these will decay to insignificant concentrations during the period of post-closure institutional control.

- The same list of 58 radionuclides was used for all 15 sites with the exception of WVDP where 18 radionuclides were evaluated; WVDP was analyzed only for disposal of radionuclides currently in inventory at the site. The permissible waste concentration was calculated individually for each radionuclide, including significant decay products, as if it contributed the entire permissible dose.

- The waste form considered was grouted MLLW treatment residuals. In the PE, a desorption mechanism with infiltrating water was used.

- Two generic disposal facility designs were considered: a RCRA compliant, below-ground trench and a RCRA-compliant, above-ground tumulus. Both facilities were assumed to be square with a plan area of 2500 m^2 (26,910 ft^2). This size was chosen to provide consistency in the analysis of all the sites, and the analysis can be modified easily to accommodate other configurations.

2.3 Transport

For each pathway the PE teams estimated the maximum permissible waste concentration at the performance boundary for each radionuclide by using the performance measures and the appropriate pathway or scenario dose conversion factors (annual effective dose equivalent per unit concentration). For the water and atmospheric pathways, the PE teams represented the attenuation of radionuclides that occurs between the waste in the disposal facility and the performance boundary as a "concentration reduction factor" (CRF). For the intruder analyses, the concentration reductions were estimated for two exposure pathways, homesteader and post-drilling, that were assumed to be appropriate for, and applicable to, all the sites. After permissible waste concentrations were calculated for the water and atmospheric pathways and the intruder scenarios, the lowest permissible waste concentration of the three was selected as limiting at that site for a particular radionuclide.

2.3.1 Water Pathway Analysis

Knowledge of groundwater flow and radionuclide movement in the water pathway at each site provided the basis for the conceptual model considered in the PE. The PE teams used a conceptual model that encompassed the current understanding of the technical staffs at each site in terms of site-specific geology, hydrology, and transport, although at sites with LLW performance assessments, the PE analysis generally did not consider as many concentration attenuation mechanisms as did the performance assessments. For the water pathway, a continuous source assumption was used, and the peak concentration of radionuclides in the groundwater could only be reduced by diluting the leachate with groundwater or surface water, and by sorption which enhances radioactive decay.

At each site, the PE teams began with a generic conceptual model to describe the water pathway (Figure 2) which was modified as necessary to reflect site-specific conditions (e.g., fracture flow or additional flow paths). While site-specific analyses such as performance assessments attempt to be conservative representations of actual site behavior, the PE water pathway analyses likely provided more conservative (i.e., lower) permissible water concentrations than performance assessments would have due to the simple and conservative transport assumptions used in the PE. Sensitivity analyses of all of the parameters were also performed.

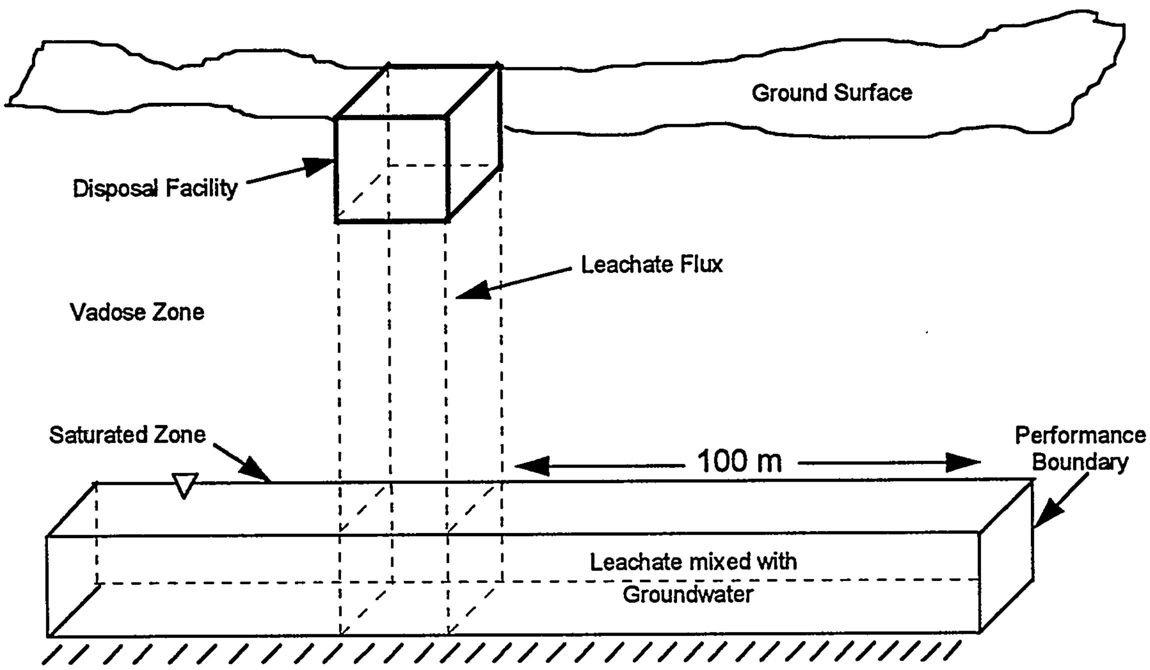


Figure 2. Generic conceptual model for the water pathway.

Leachate (radionuclides dissolved in water) was assumed to be generated by water flowing through the disposal facility at a rate that was controlled by the assumed performance of the disposal facility. When all engineered barriers had failed, the rate was assumed to equal the natural recharge through local soils. The volumetric flow rate of water through the disposal facility was based on the assumed performance and size of the disposal facility. No lateral spreading was assumed, so the leachate flux through the unsaturated zone was confined to the soil column directly below the facility. No dilution was assumed to occur in the unsaturated zone, so at steady state, the concentration that reached groundwater eventually equaled the leachate concentration. As contaminated water entered the saturated zone, the contaminant was assumed to mix with clean groundwater, resulting in dilution within the aquifer.

2.3.2 Atmospheric Pathway Analysis

The PE teams used a conceptual model for evaluating the atmospheric pathway that was derived from performance assessments for LLW disposal facilities. The model was generalized for the PE but used site-specific values for several of the input parameters. Of the radionuclides considered in the PE, only H-3 and C-14 were expected to be volatile for the disposal facility conditions and thus were the only radionuclides considered in the PE for atmospheric transport. Other radionuclides such as I-129 and Cs-137 may become volatile under high temperature conditions, but such conditions are not expected to be present in waste disposal facilities.

For the atmospheric pathway, the peak concentrations of airborne radionuclides were assumed to be reduced by upward diffusion through the soil above the disposal facility, by mixing in the ambient air above the facility, by dispersion through the atmosphere to the performance boundary, and by radioactive decay. The approach taken by the PE teams was to use a diffusion mechanism with conservative parameter values. This was done to bound results from other, harder-to-quantify release mechanisms (e.g., soil desiccation and cracking, burrowing animals, and plant root uptake).

At each site, the PE teams used a generic conceptual model to describe the atmospheric pathway (Figure 3). In the model, radionuclides were assumed to be transported from the disposal facility through the soil diffusion zone to the soil surface by vapor (tritiated water) and gaseous (carbon dioxide containing the C-14 isotope) diffusion. After reaching the soil surface, the radionuclides were assumed to be entrained in the air as volatiles. Once airborne, the radionuclides were subsequently assumed to be transported in the atmospheric dispersion zone to a receptor located at the performance boundary. Two components of the atmospheric pathway were individually evaluated: the zone from the top of the disposal facility to the soil surface, in which upward movement of the radionuclides occurred by diffusion; and the zone encompassing emission of the radionuclide to the atmosphere, mixing with the ambient air above the disposal facility, and subsequent transport and dispersion downwind to the performance boundary.

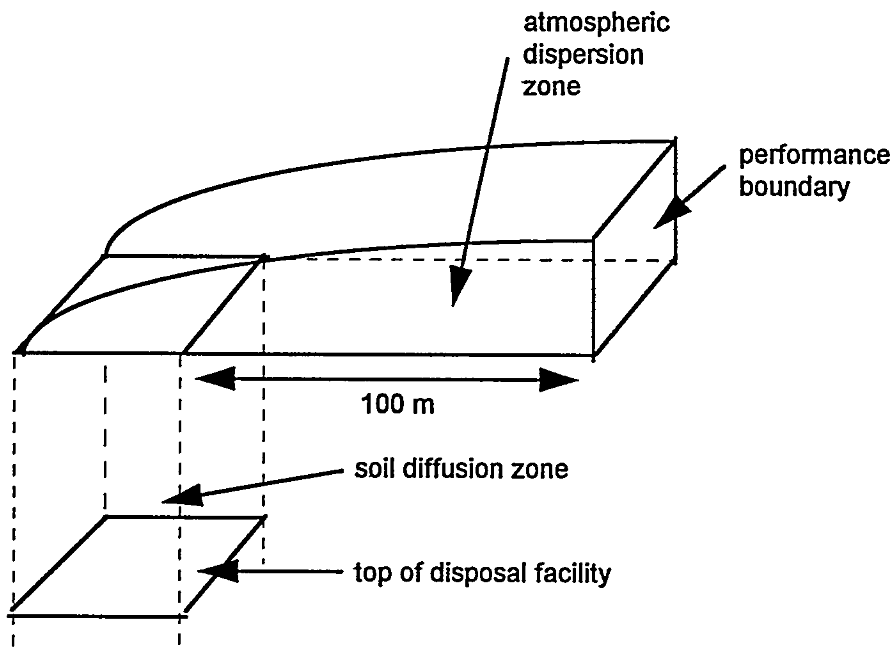


Figure 3. Generic conceptual model for the atmospheric pathway.

The arrival time of radionuclides at the performance boundary was assumed to be 100 y based on the following generic assumptions of the PE:

- The waste form was grouted MLLW treatment residuals. Based on this assumption, tritium as vapor was bound in the pore water of the hydrophilic grout, and formation of carbon dioxide as a gas carrying the C-14 isotope was limited by the high pH of the grout, so that the waste form provided retention of these volatile radionuclides in the disposal facility.

- The disposal facility was capped by a RCRA-compliant cover system. Based on this assumption, the cover system was maintained to provide low permeability for 100 y.

2.3.3 Analysis of Inadvertent Human Exposure Scenarios

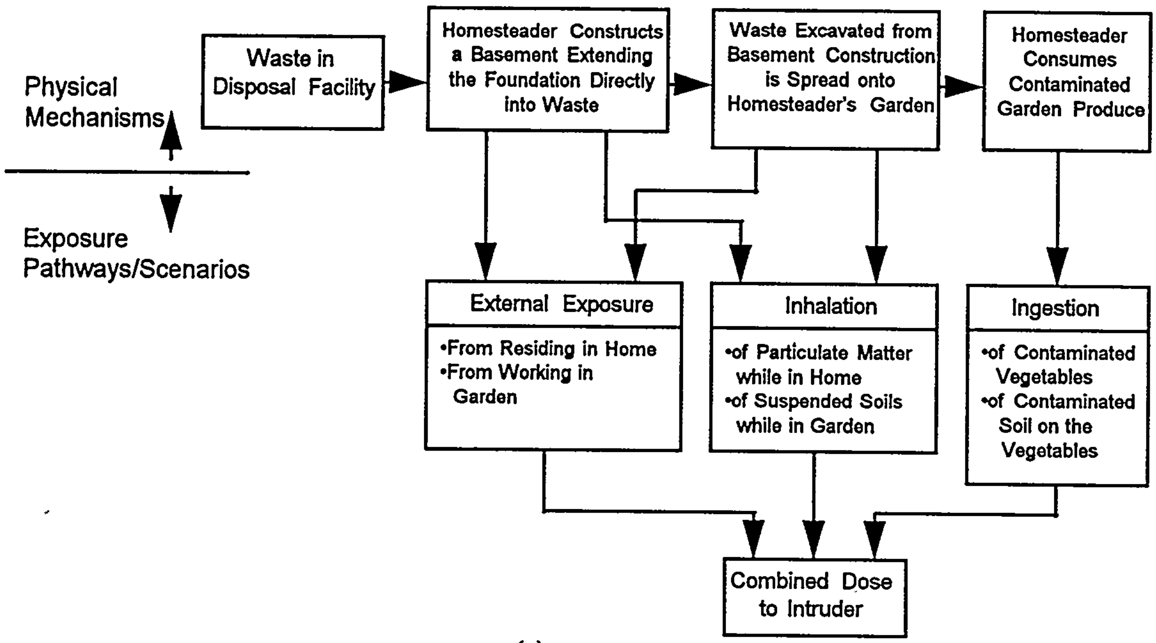
The PE teams used standard intrusion scenarios that were developed for performance assessments of LLW disposal facilities. Although future social behaviors, including intrusion scenarios, are difficult to predict, two long-term, chronic exposure scenarios were considered in the PE: the agricultural (homesteader) scenario and the post-drilling scenario (Figure 4). Any variations in these scenarios were based on information provided by site personnel on factors such as the types of activities that reasonably could lead to exposure to buried waste at the site, and the effectiveness of active or passive institutional controls and engineered barriers in precluding access to the waste.

The agriculture (homesteader) scenario encompassed the establishment by an intruder of a permanent homestead directly above a disposal facility with the foundation of the home extending into the waste. As part of the scenario, a portion of the waste exhumed from the disposal facility was assumed to be mixed with native soil in the intruder's vegetable garden.

The post-drilling scenario involved the construction by an intruder of a well for a domestic water supply. The well was assumed to be drilled through the disposal facility and the cuttings were mixed with native soil in the intruder's vegetable garden. The intruder was assumed to garden in some of the exhumed waste but did not reside permanently above the disposal facility. An important difference between the two scenarios is that the amount of material brought to the surface and subsequently mixed into the intruder's garden is about an order of magnitude less for the post-drilling scenario than for the homesteader scenario. In addition, the post-drilling scenario was assumed to occur earlier following closure.

In the PE, the dose resulting from an intrusion scenario (the sum of the doses from all exposure pathways involved in that scenario) per unit concentration was estimated using scenario dose conversion factors that were applied to specific exposure pathways. The values for these conversion factors were radionuclide-specific and facility-design-specific and were the same for all sites. Estimates of the reductions due to radioactive decay were based on the time of intrusion into the disposal facility.

Unless modified by site-specific conditions, the time of intrusion for the homesteader scenario was assumed to be 300 y after facility closure for the trench design and 500 y after closure for the tumulus design; the time of intrusion for the post-drilling scenario was assumed to be 100 y after closure. These times of earliest intrusion involve assumptions that intact engineered barriers preclude intrusion by excavation beyond the 100-y period of active institutional control. A site-specific modification of the generic intrusion scenarios was used at the Savannah River Site. Based on the approach used in the site-specific performance assessment for LLW, the post-drilling scenario was assumed to occur at a later time. In this region of soft-rock formations, a water-well driller who encountered the hard grout/concrete of the stabilized waste was assumed to move to a location of easier drilling. In this case, the time of occurrence for the post-drilling scenario was delayed to 300 y after closure for the trench facility and 500 y after closure for the tumulus facility.



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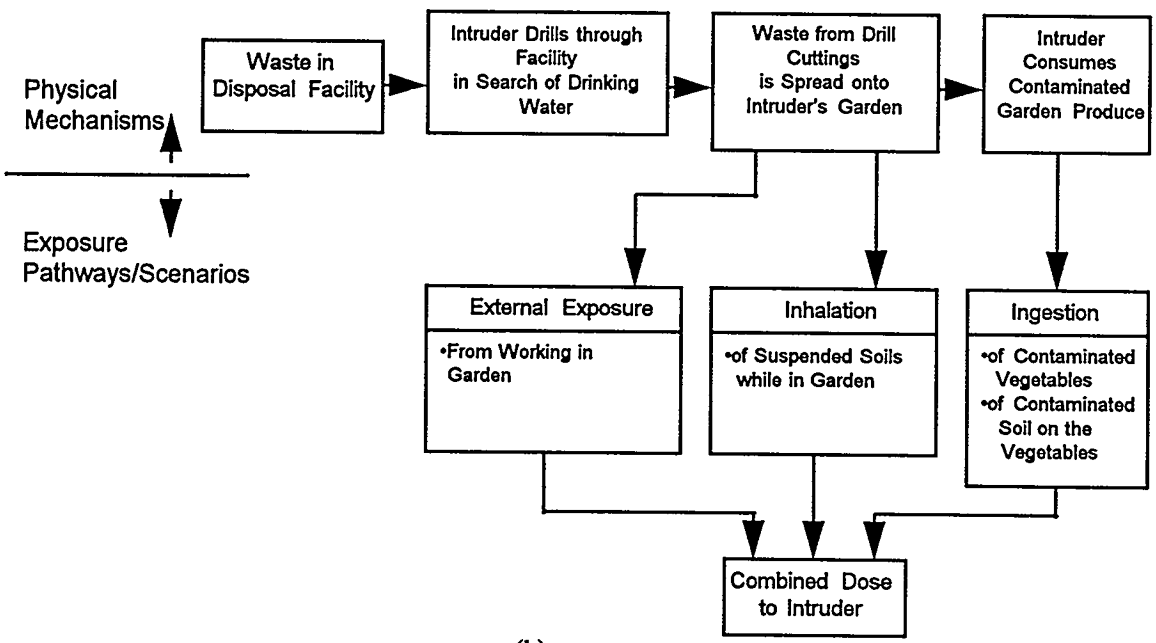


(b)

Figure 4. Exposure pathways in the PE for the (a) homesteader and (b) post-drilling intrusion scenarios.

2.4 Outputs of the Analyses

The outputs of the analyses for the release and exposure scenarios are estimates of permissible radionuclide concentrations in waste averaged over the entire disposal facility. These concentrations should not be interpreted as package-scale concentrations.

3.0 PE RESULTS

This section summarizes the results for the three pathways analyzed as part of the PE at each of the 15 DOE sites. Details about the PE analysis and results for each individual site are presented in the 15 site chapters in Volume 3 of this report, and the results from the 15 sites are compiled and discussed together in Chapter 7 of Volume 2.

Each radionuclide has characteristics that make its behavior in the environment and its toxicity unique. However, there are sufficient commonalities among many of the nuclides considered in the PE to allow grouping by their major characteristics. To facilitate the discussion in this summary of radionuclide behavior at the 15 DOE sites, the 58 radionuclides evaluated in the PE were grouped into 8 different categories according to persistence (i.e., half-life), mobility, and radiotoxicity. An indicator radionuclide was then chosen to represent each of the 8 categories (Table 1). Following the discussion of site-specific radionuclide behavior utilizing indicator radionuclides, a discussion encompassing all 58 radionuclides is provided.

Table 1. Characteristics of the Indicator Radionuclides

Radionuclide	Half-Life (years)		Mobility	Radiotoxicity
H-3	Short	12.3	High and Volatile	Low
C-14	Medium	5700	High and Volatile	Low
Sr-90	Short	29.1	High	Medium
Tc-99	Long	213,000	High	Low
Cs-137	Short	30.2	Medium	Medium
U-238	Long	4.47 billion	Medium	Medium
Pu-239	Long	24,100	Low	High
Am-241 (Np-237) [a]	Medium (Long)	433 (2.14 million)	Low (High)	High (High)

Half-life - Short: $t_{1/2} \leq 30$ y; Medium: $30 < t_{1/2} \leq 10{,}000$ y; Long $t_{1/2} > 10{,}000$ y

Mobility - High: $K_d \leq 5$ mL/g; Medium: $5 < K_d \leq 100$ mL/g; Low: $K_d > 100$ mL/g

Radiotoxicity - Low: PDCF ≤ 1 (rem/y)/(μCi/L); Medium: 1 < PDCF ≤ 100 (rem/y)/(μCi/L); High: PDCF > 100 (rem/y)/(μCi/L)

a Buildup and decay of the Np-237 decay product of Am-241 over time is taken into account in the analysis for Am-241 as an indicator radionuclide. The Np-237 in the original disposed waste is included in the category with Tc-99 as the indicator radionuclide.

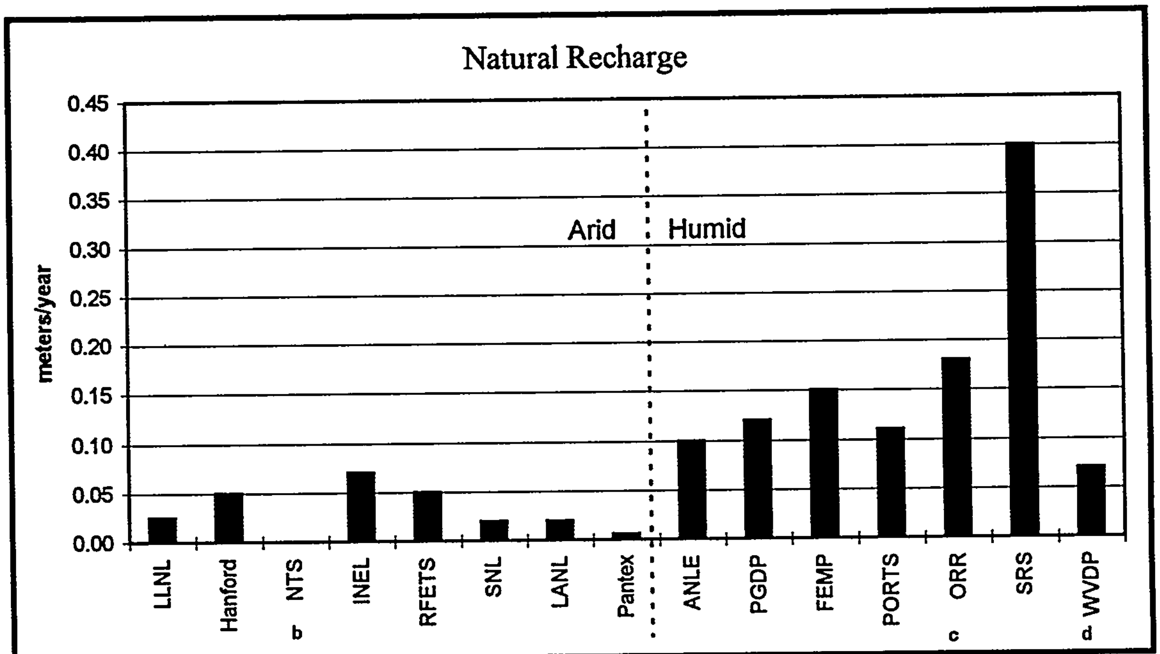
3.1 Results of Water Pathway Analysis

The performance evaluations showed that the estimates of permissible radionuclide concentrations in the waste, based on the water pathway, were highly dependent on some of the natural characteristics of the site. These included the natural recharge, depth-to-groundwater, and subsurface geology. Of these, the natural recharge is directly affected, and the depth-to-groundwater is affected to some extent, by the climate of the region in which the disposal facility is located. For this reason, the 15 sites were divided into arid and humid groups, with the former including LLNL, Hanford, NTS, INEL, RFETS, SNL, LANL, and Pantex, and the latter including ANLE, PGDP, FEMP, PORTS, ORR, SRS, and WVDP.

The natural recharge limits the amount of water available to leach and move the waste through the subsurface as well as the amount of groundwater for dilution. A large amount of water moving through the disposal facility and the unsaturated zone will provide a large volume of leachate to mix with the aquifer. This in turn may result in less dilution when the leachate mixes with the groundwater (see Figure 2). A low natural recharge, in contrast, will tend to produce conditions leading to a smaller volume of leachate and a higher dilution by groundwater. The natural recharge also tends to affect how fast the water and its accompanying radionuclides will move through the unsaturated zone to the groundwater, and it affects to some extent the depth to groundwater. The range of natural recharge found at the 15 sites is shown in Figure 5. In general, arid sites have low natural recharge due to low precipitation and high potential evapotranspiration rates, and humid sites have high natural recharge.

The depth to groundwater at a site affects the time required for water and any accompanying radionuclides to reach the groundwater. In general, the deeper the water table, the longer it takes water and radionuclides to migrate from the facility to the groundwater, resulting in greater decay of radionuclides. As shown in Figure 5, about half of the 15 sites that were evaluated have deep water tables (greater than 50 m [164 ft]), while the remainder have water tables that are close to the ground surface. Typically, arid sites have deep water tables and humid sites have shallow water tables.

The physical characteristics of the subsurface geology also affect the ability of porous media to transmit water, and hence, the travel times for migration through the subsurface to the performance boundary. For example, fractured media can transmit water and radionuclides quickly through an aquifer under saturated conditions, but under unsaturated conditions fractures tend to impede flow. Three of the sites evaluated, LANL, ORR, and WVDP, have fractured media in the unsaturated zone, and Pantex has a surface soil horizon with an enhanced potential for preferential flow paths. To simplify the analysis, these sites were modeled by removing the fractured zones from the soil column. The sites at ANLE and ORR have fractured media in the saturated zone. These sites were modeled with an effective porosity which accounted for the fractures.

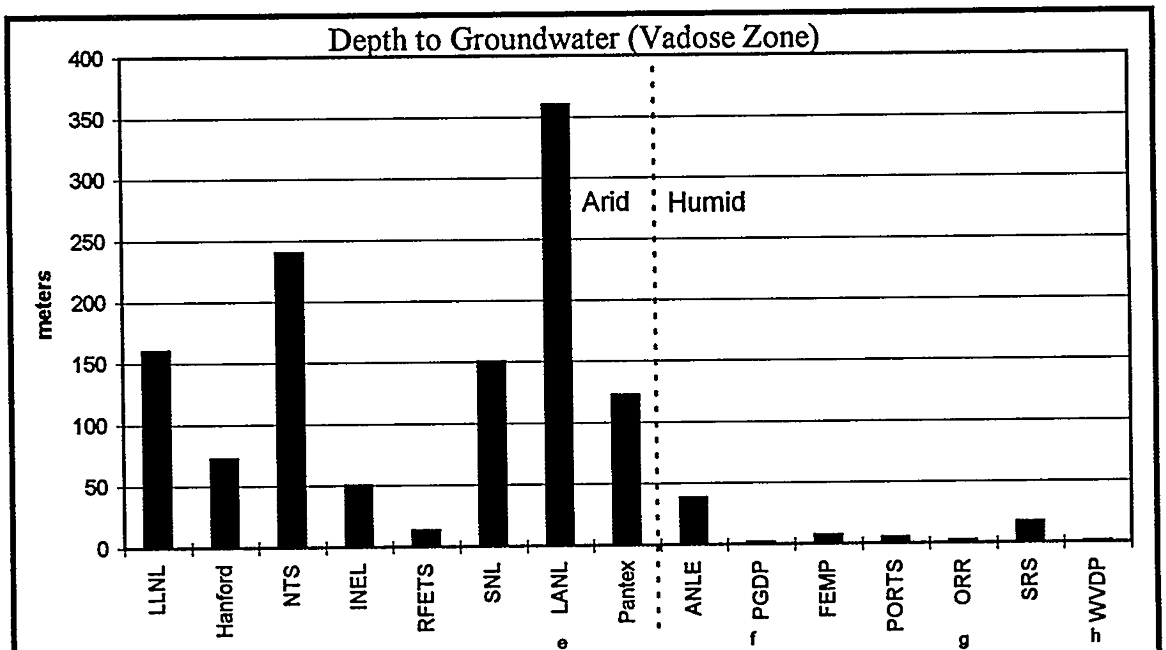


a A range of values was used in the LLW performance assessment for the 200 East Area at Hanford. This value represents an upper bound estimate.

b The draft performance assessment indicates a lack of net downward migration at NTS.

c Infiltration through the disposal facility due to contributions from up-slope runoff is estimated to be 2.2 m/y, with deep vertical infiltration approximately 0.18 m and the remaining as lateral flow.

d Natural infiltration rate is 0.07 m/y, with vertical deep infiltration approximately 0.01 m/y and the remaining infiltration flowing laterally.



e Vadose zone thickness used in the PE is 333 m, which is the result of not considering 27 m of fractured tuff in the transport analysis.

f Vadose zone thickness used in the PE is 15.5 m, which is the result of adding 1.5 m of unsaturated material to 14 m of saturated media in which transport is predominantly vertical.

g Vadose zone thickness used in the PE is 0 m, which is the result of not considering 2 m of fractured saprolite in the transport analysis.

h Vadose zone thickness used in the PE is 0 m, which is the result of not considering 1 m of material in the transport analysis.

Figure 5. Selected characteristics of the 15 sites.

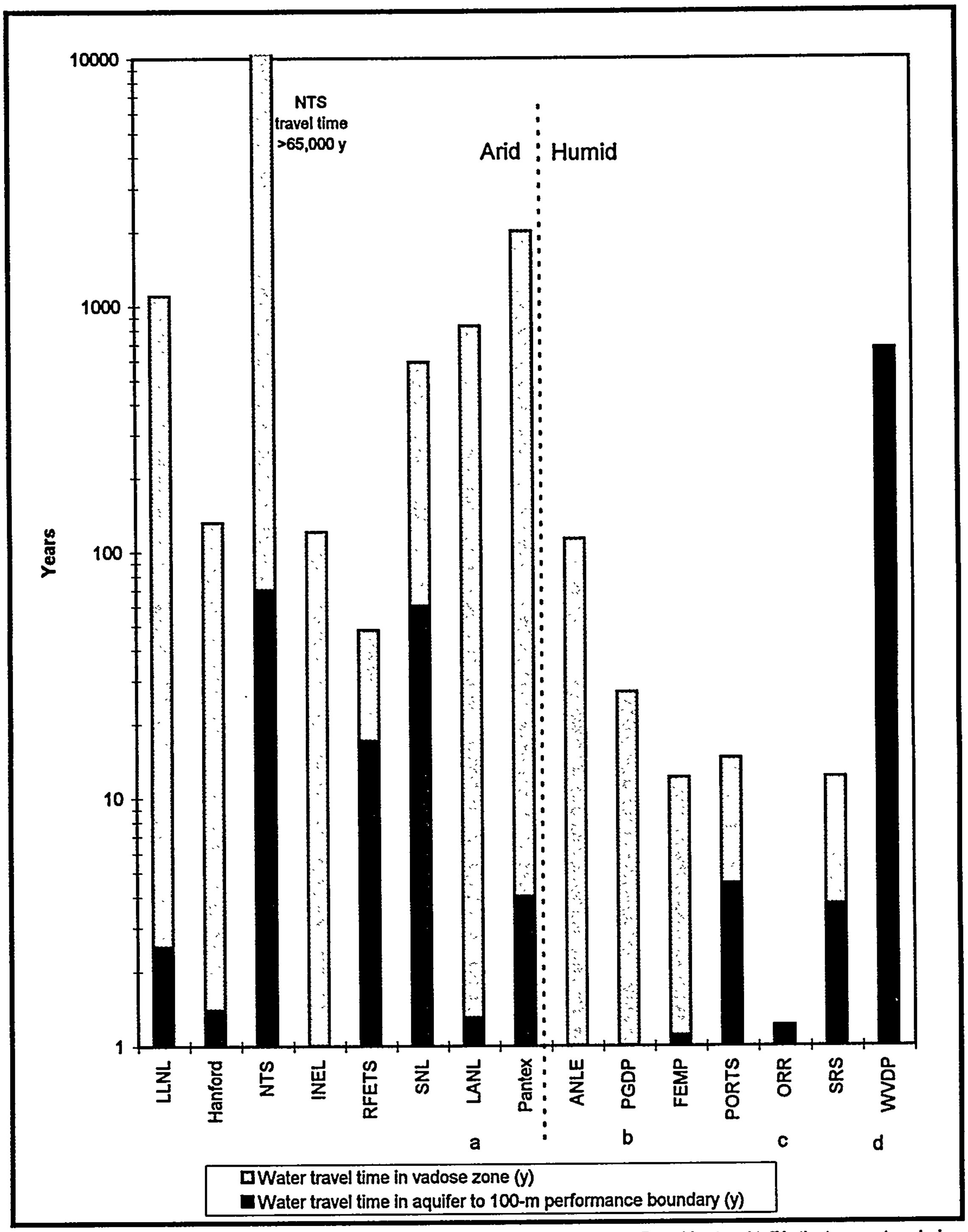
The estimated subsurface water travel time for each of the 15 sites is shown in Figure 6. Subsurface water travel times are slightly longer for the tumulus design because the pathway is longer (the trench is an excavated facility while the tumulus is a surface facility). Most of the arid sites have much longer subsurface travel times than the humid sites, primarily due to the low natural recharge and large depths to groundwater. For most sites, especially those in arid regions, the estimated water travel time in the vadose zone was far greater than in the saturated zone. At Hanford, the estimated 100-y of water travel time is the minimum expected; travel times in excess of 1000 y are likely in the burial grounds area. The WVDP site had an estimated long water travel time for the saturated zone due to the very low hydraulic conductivity of the subsurface formations at that site.

Some geologic formations can significantly reduce the mobility of radionuclides. For example, a sand containing clay that has a high sorptive capacity will sorb and retard some radionuclides so that radionuclide transport through this formation will be slower than through a clean sand formation. In both cases, the radionuclides will travel more slowly than the water.

The permissible waste concentrations for each of the indicator radionuclides based on analyses of the water pathway for the 15 sites are shown in Figure 7 for both the trench and tumulus designs. A summary of the permissible waste concentrations is presented in Table 2. Some radionuclides listed in Figure 7 have no limit (NL), meaning that, for the highest possible radionuclide concentration in the waste (i.e., the specific activity of the pure isotope), the water pathway produced a dose at the performance boundary of less than 4 mrem/y (0.04 mSv/y), and therefore, the permissible waste concentration was considered unlimited. In addition, arrival times for some of the indicator radionuclides listed in Figure 7 were beyond the 10,000-y performance period. The estimated waste concentrations for these radionuclides are presented in Figure 7 for information purposes only; these values were not considered in determining the most restrictive disposal limit from among the evaluated pathways.

Sites with radionuclides having high or unlimited permissible waste concentrations may have a greater capability to dispose of those radionuclides. For the long-lived indicator radionuclides (C-14, Tc-99, U-238, Pu-239, and Am-241 [as Np-237]), the permissible waste concentrations for the generic tumulus are twice those of the generic trench because the trench is assumed to contain twice as much waste per unit volume of the facility, and radioactive decay is minor. In addition, little radioactive decay will have occurred during detention in either facility. Permissible waste concentrations for short-lived indicator radionuclides (H-3, Sr-90, and Cs-137) are higher for the tumulus than for the trench design due to the ability of the tumulus design to retain the radionuclides and permit them to decay.

For the water pathway, only the long-lived, highly mobile radionuclides such as Tc-99 have low permissible waste concentrations at all sites. Short-lived radionuclides (H-3, Sr-90, Cs-137, and Am-241) are associated with high or unlimited permissible waste concentrations at all sites because these radionuclides decay significantly prior to arrival at the performance boundary. Long-lived radionuclides with low mobility such as Pu-239, or medium-lived, high mobility radionuclides, such as C-14, have relatively high permissible waste concentrations at most arid sites and relatively low permissible waste concentrations at most humid sites.



a Vadose zone thickness used in the PE is 333 m, which is the result of not considering 27 m of fractured tuff in the transport analysis.

b Vadose zone thickness used in the PE is 15.5 m, which is the result of adding 1.5 m of unsaturated material to 14 m of saturated media in which transport is predominantly vertical.

c Vadose zone thickness used in the PE is 0 m, which is the result of not considering 2 m of fractured saprolite in the transport analysis.

d Vadose zone thickness used in the PE is 0 m, which is the result of not considering 1 m of material in the transport analysis.

Figure 6. Subsurface water travel times.

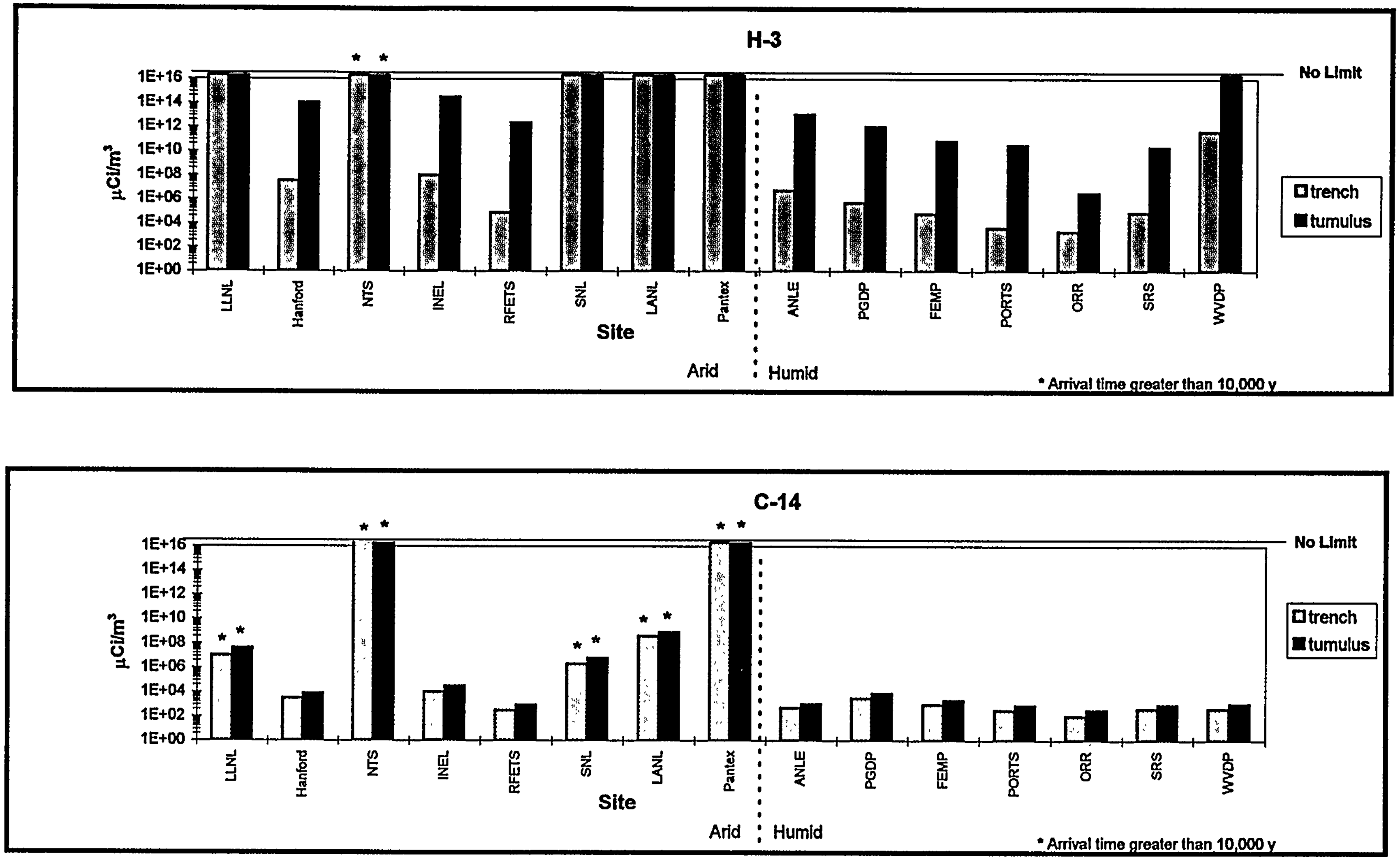
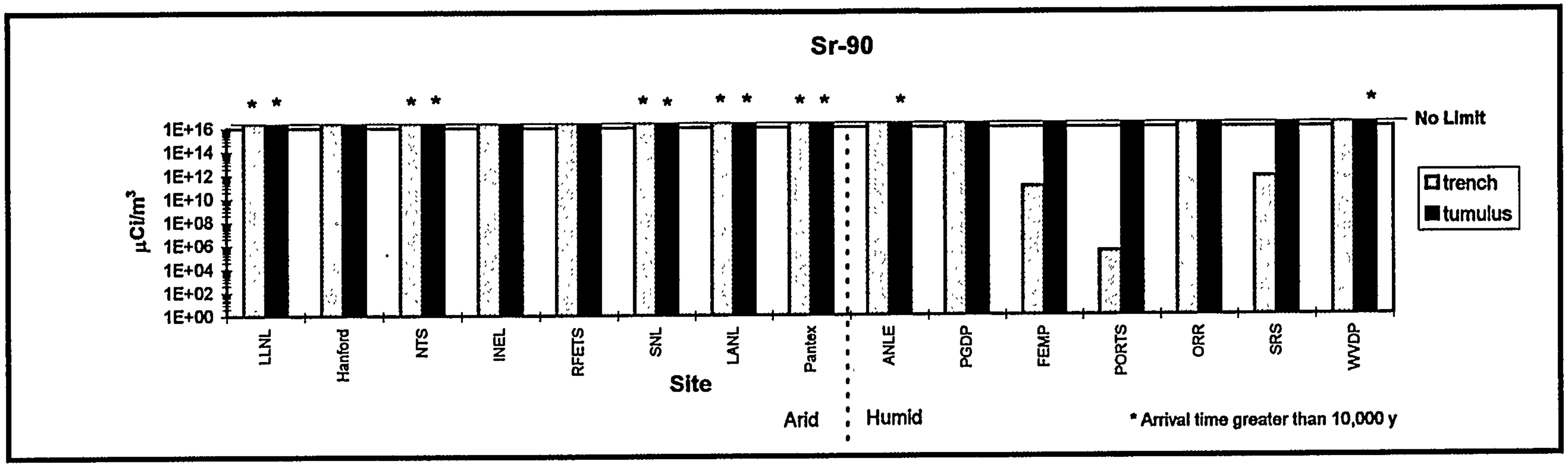


Figure 7. Permissible Waste Concentrations ($\mu Ci/m^3$) for the Water Pathway. (Part 1 of 4)



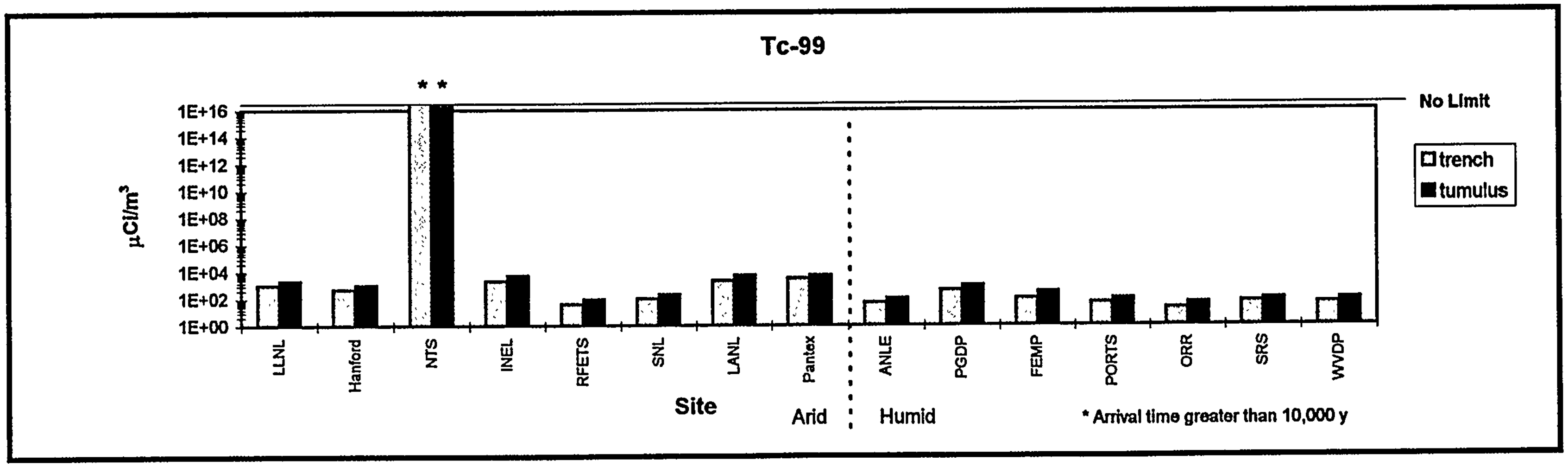
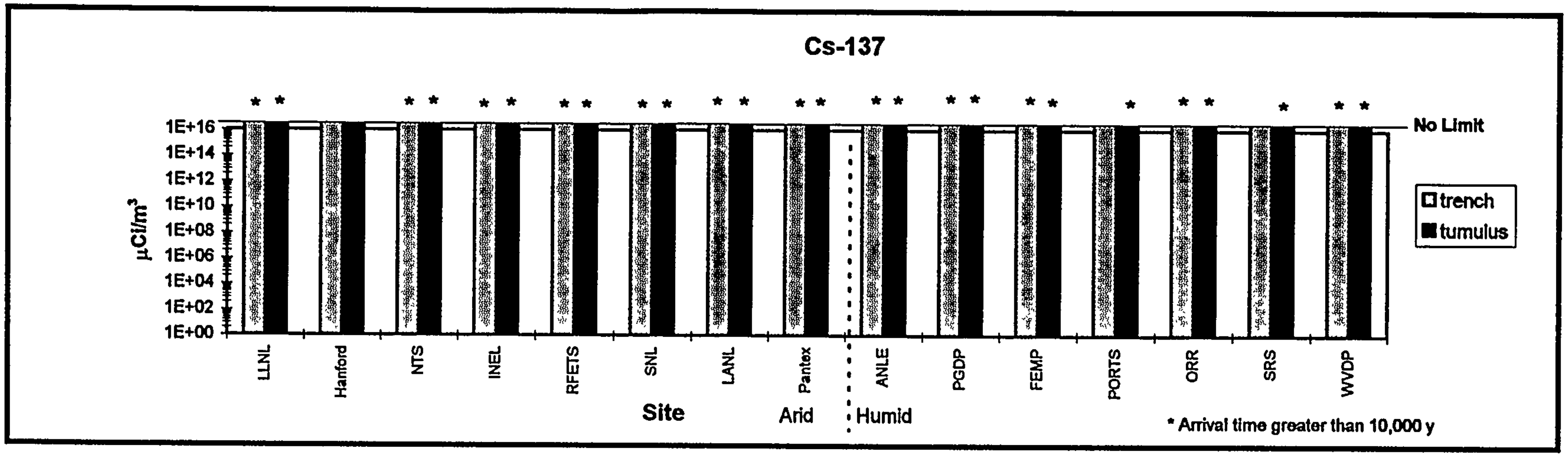


Figure 7. Permissible Waste Concentrations ($\mu Ci/m^3$) for the Water Pathway. (Part 2 of 4)



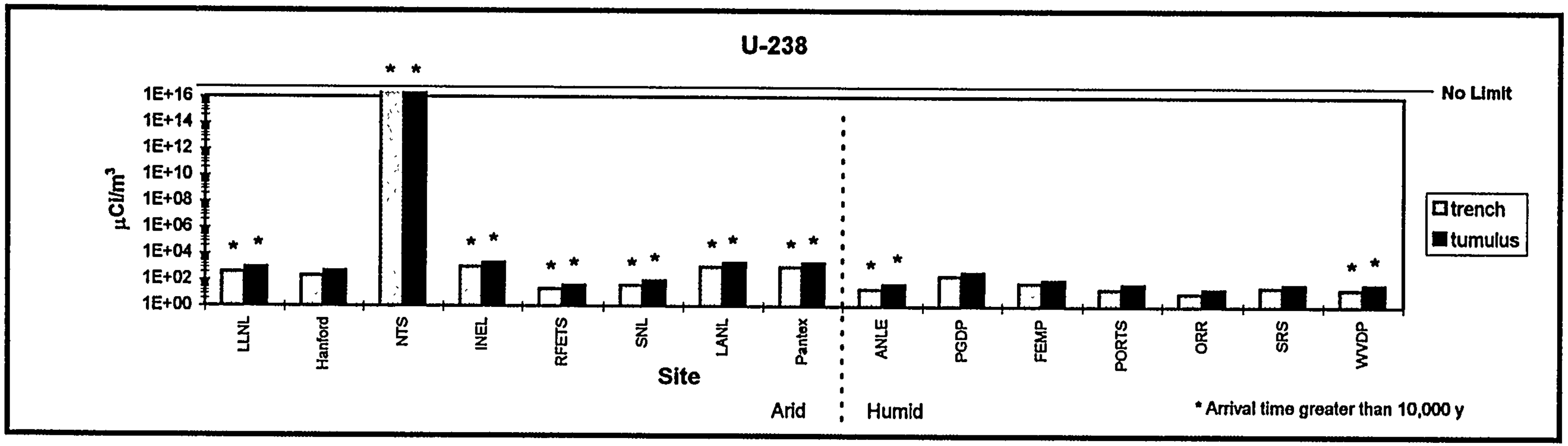
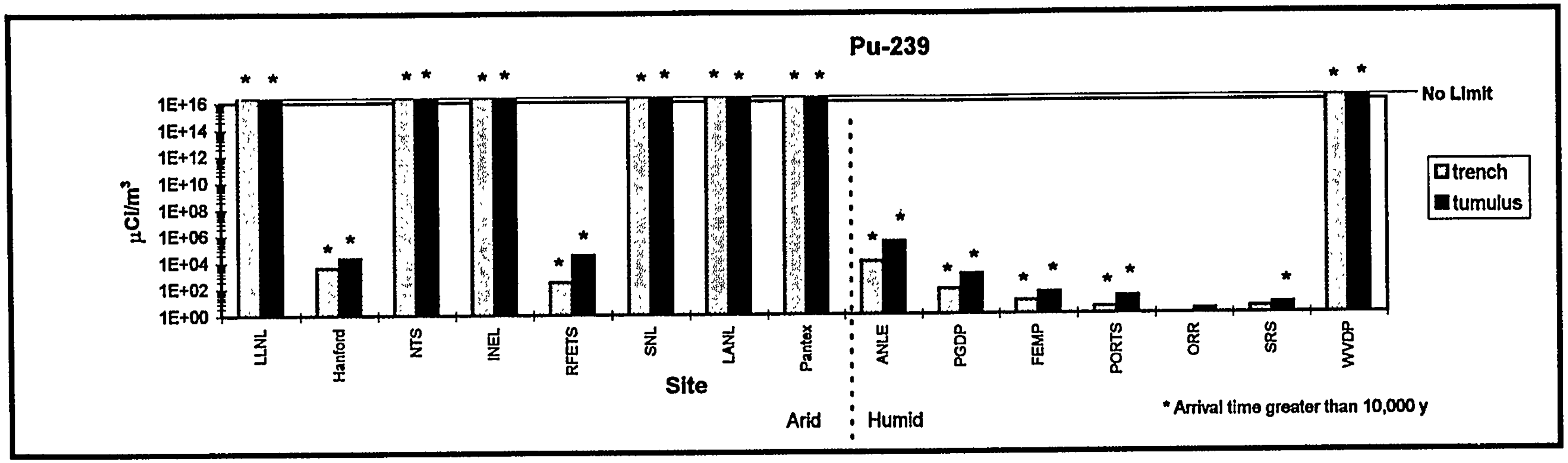


Figure 7. Permissible Waste Concentrations ($\mu Ci/m^3$) for the Water Pathway. (Part 3 of 4)



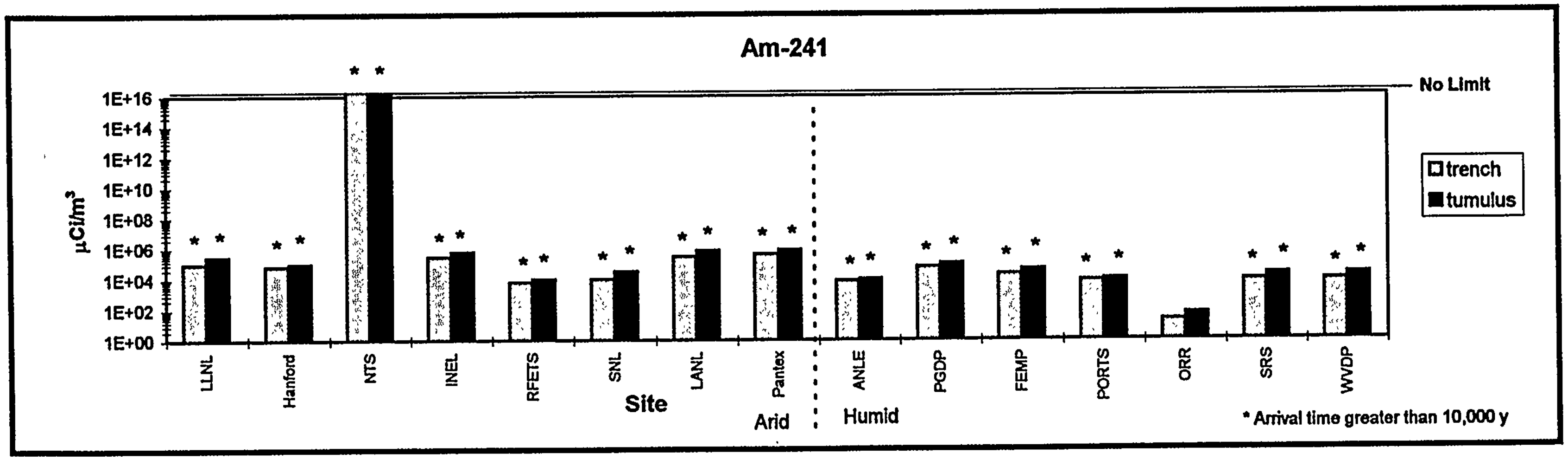


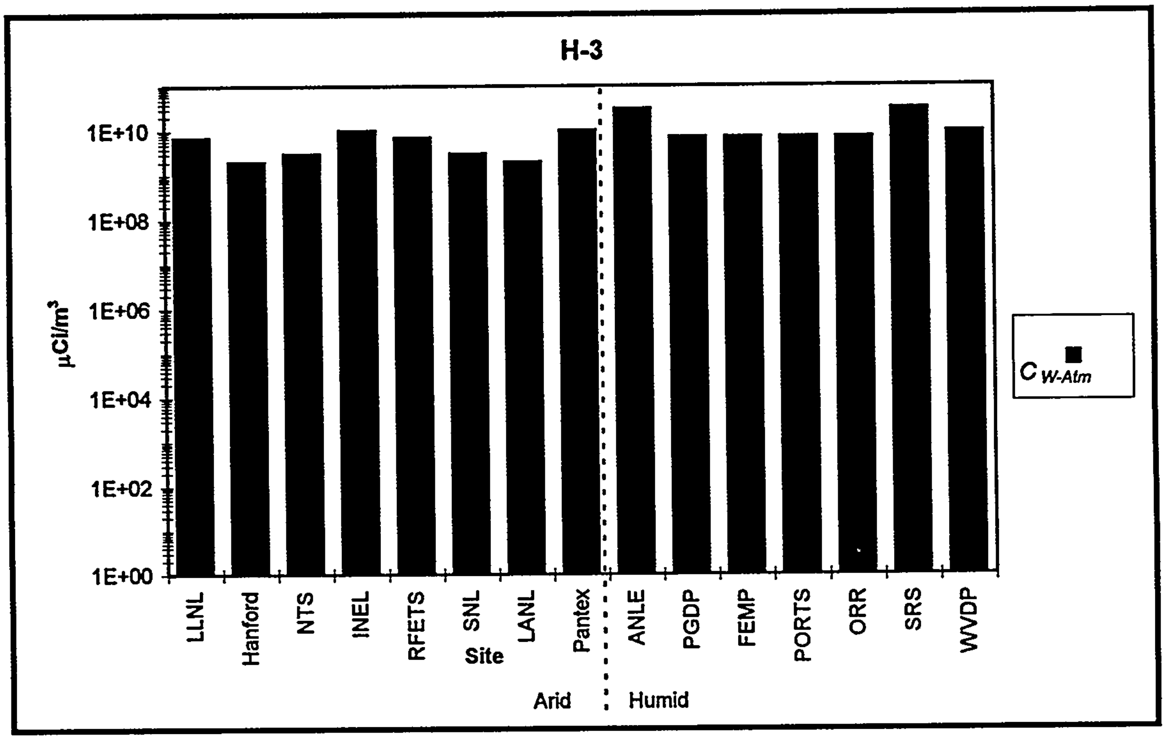
Figure 7. Permissible Waste Concentrations ($\mu Ci/m^3$) for the Water Pathway. (Part 4 of 4)

Table 2. General Summary of Permissible Waste Concentrations for the Water Pathway

INDICATOR RADIONUCLIDE	GENERAL RESULT
H-3 (short-lived, high mobility and volatile)	High permissible concentrations (often unlimited) at arid sites. Relatively high permissible concentrations at humid sites.
C-14 (medium-lived, high mobility and volatile)	High permissible concentrations at sites with long water travel times (LLNL, SNL, LANL, and Pantex), no limit for arrival times beyond 10,000 y (NTS). Low permissible concentrations at all other sites.
Sr-90 (short-lived, moderate mobility)	Unlimited in tumulus at all sites. Limited in trench design for FEMP, PORTS, and SRS.
Tc-99 (long-lived, high mobility)	Low permissible concentrations at all sites except NTS, which has no limit. Arid site permissible concentrations generally greater than humid sites.
Cs-137 (short-lived, low mobility)	Unlimited at all sites.
U-238 (long-lived, generally low mobility but high mobility at Hanford)	Relatively low permissible concentrations at all sites. No limit for arrival times greater than 10,000 y for most arid sites as well as ANLE and WVDP.
Pu-239 (long-lived, low mobility)	High or unlimited permissible concentrations at all arid sites. No limit for arrival times greater than 10,000 y for most humid sites. Low permissible concentrations at ORR and SRS.
Am-241 (medium-lived, low mobility) - decays to Np-237 (long-lived, high mobility)	Am-241 decays prior to arrival at the performance boundary and Np-237 arrives at the performance boundary beyond 10,000 y at all arid sites except RFETS. Higher permissible concentrations at all humid sites except ORR. WVDP tumulus concentration not limited.

3.2 Results of Atmospheric Pathway Analysis

Two volatile radionuclides, H-3 and C-14, were analyzed for the atmospheric pathway. Their permissible waste concentrations for the atmospheric pathway for each of the 15 sites are shown in Figure 8. The results for the atmospheric pathway are the same for the trench and tumulus designs because no differences between the disposal technologies were accounted for in the analyses. Even though site specific data were used in the calculations, there are no significant differences in the permissible concentrations for each of these two volatile radionuclides at the 15 sites because the atmospheric pathway analysis was basically generic. Because of its short half-life, the permissible concentration limits for H-3 are much higher than those for C-14.



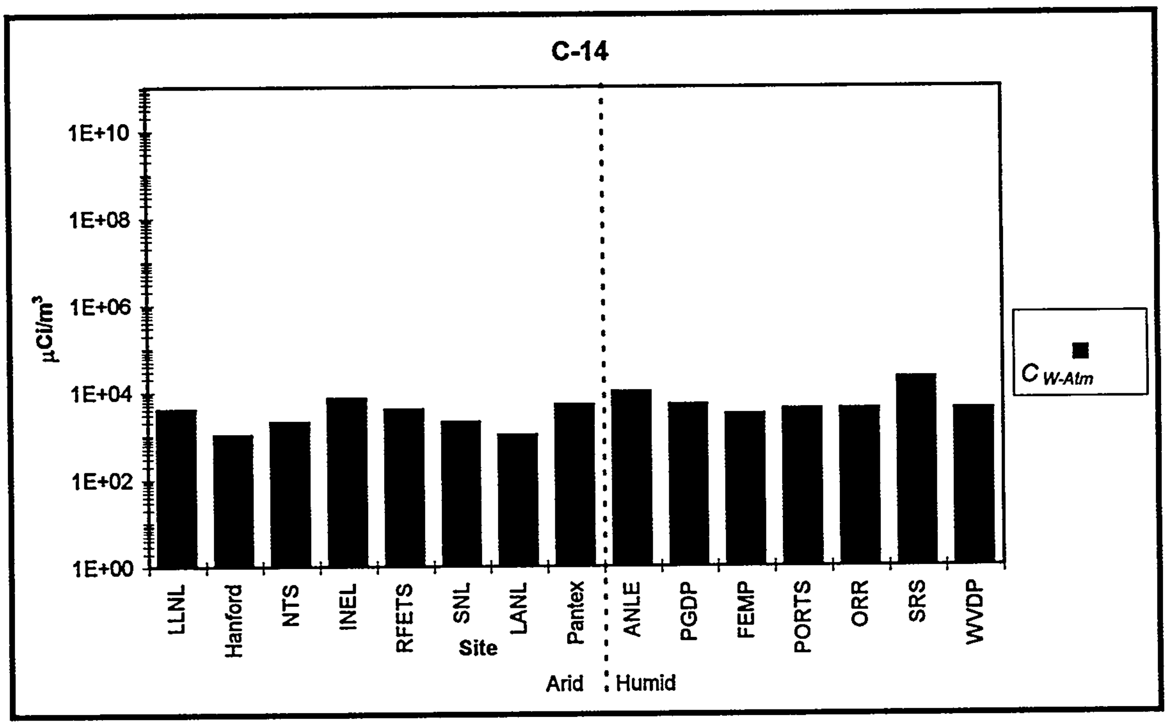


Figure 8. Permissible waste concentrations ($\mu Ci/m^3$) for H-3 and C-14 for the atmospheric pathway.

3.3 Results of Inadvertent Human Exposure Analysis

The estimated permissible waste concentrations based on analyses of the intruder scenarios were the same at all sites except SRS. At SRS, the drilling practices for water-well construction are believed to delay intrusion by the post-drilling scenario, resulting in higher permissible concentrations for some radionuclides. As may be noted (Figure 9), the post-drilling scenario generally yielded more restrictive waste limits than the homesteader scenario for the short-lived radionuclides (i.e., H-3, Sr-90, and Cs-137), except for trench disposal of Cs-137, primarily due to the earlier assumed time of intrusion for this scenario. In the case of the long-lived radionuclides, there is little difference between the trench and tumulus designs in the permissible waste concentrations for intrusion because the radioactive decay is minor for the differences in assumed intrusion times for the two facilities. In all cases, the permissible concentrations for the long-lived radionuclides are more restrictive for the homesteader than for the post-drilling scenario because, with the homesteader scenario, the individual is exposed to a greater volume of exhumed waste and more exposure pathways than in the post-drilling scenario.

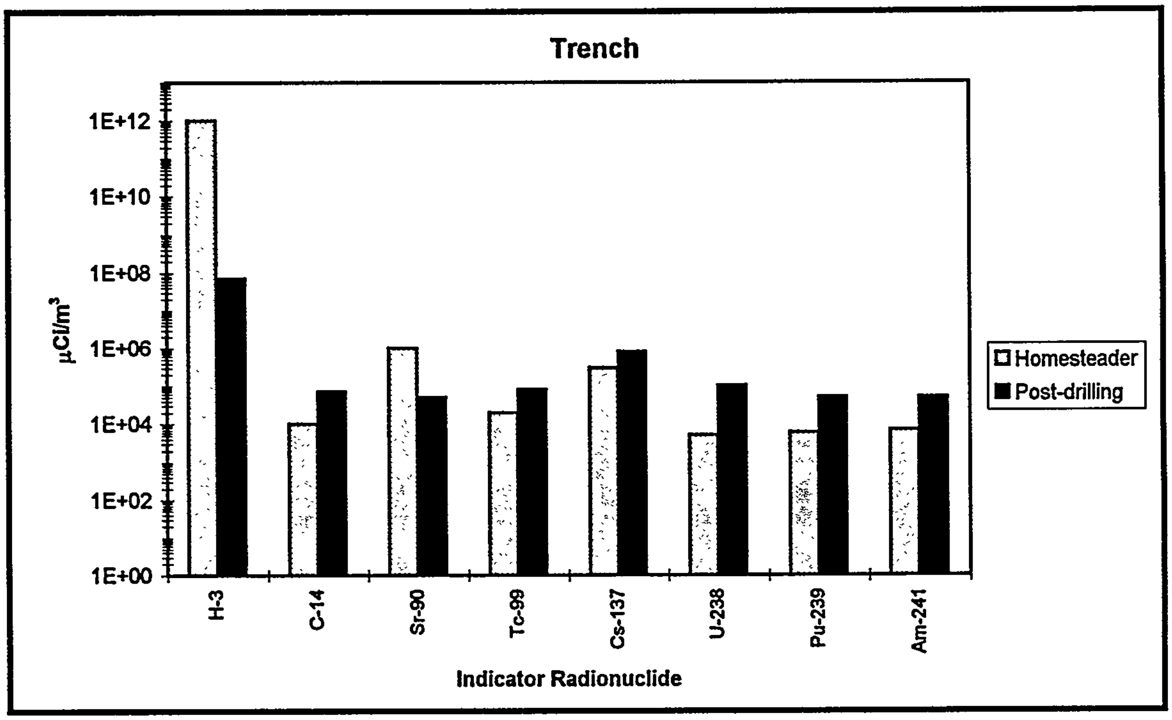
For all of the indicator radionuclides except C-14 and Tc-99, the permissible waste concentrations for the two intrusion scenarios used in the PE were similar to those established by the NRC for Class A LLW. These results are similar because the PE analysis considered scenarios that were largely similar to those used as the basis for the NRC regulations.

3.4 Comparison of the Three Pathways

The trends in performance of the 15 sites for the three exposure pathways have been summarized in the previous sections using indicator radionuclides. In this section, a discussion encompassing the 58 radionuclides is provided.

Subsequent to the calculation of the permissible concentrations for each of the radionuclides for each of the three pathways at each of the 15 sites, the lowest permissible concentration was selected as the limiting concentration at each site. The general trend in the number of radionuclides limited by the water and atmospheric pathways and the intrusion scenarios at each site is shown in Figure 10. The limiting pathway for each radionuclide at each site is summarized in Table 3. Blank cells in the table indicate radionuclides that are limited by intrusion.

Because generic intrusion analyses were applied at all sites except SRS, the sites where the water and atmospheric pathways were limiting provide a useful means for comparing the relative importance of these two pathways. At arid sites the few radionuclides that were not limited by the intrusion scenarios were those, such as Tc-99, that have long half-lives and high mobility in water. At humid sites the number of radionuclides limited by the water pathway is larger principally due to short travel times to the performance boundary. However, even at these sites the permissible concentrations of more than half of the radionuclides are limited by the intrusion scenarios. The one exception is ORR, which has the shortest groundwater travel time of any of the sites considered. As a result, approximately two-thirds of the radionuclides at that site are limited by the water pathway.



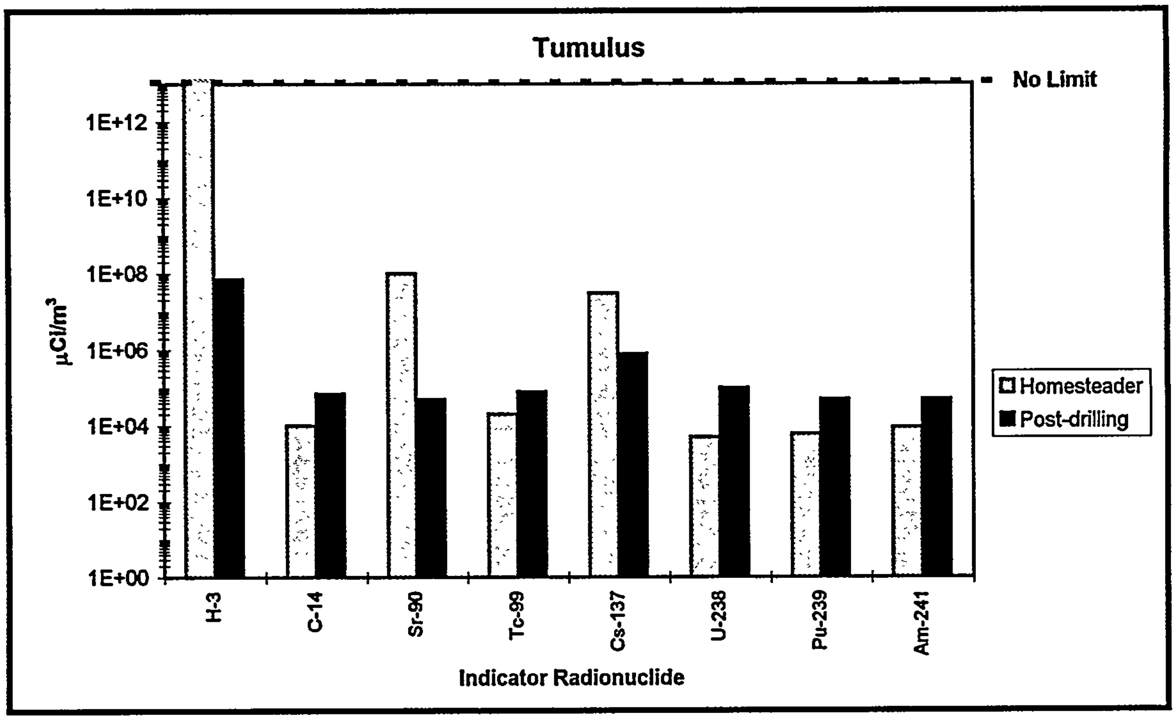


Figure 9. Permissible waste concentrations ($\mu Ci/m^3$) for the trench and tumulus designs for the standard intrusion scenarios. At SRS, the concentrations for H-3 and Sr-90 are higher for both facility designs, and the concentration for Cs-137 is higher for the tumulus design.

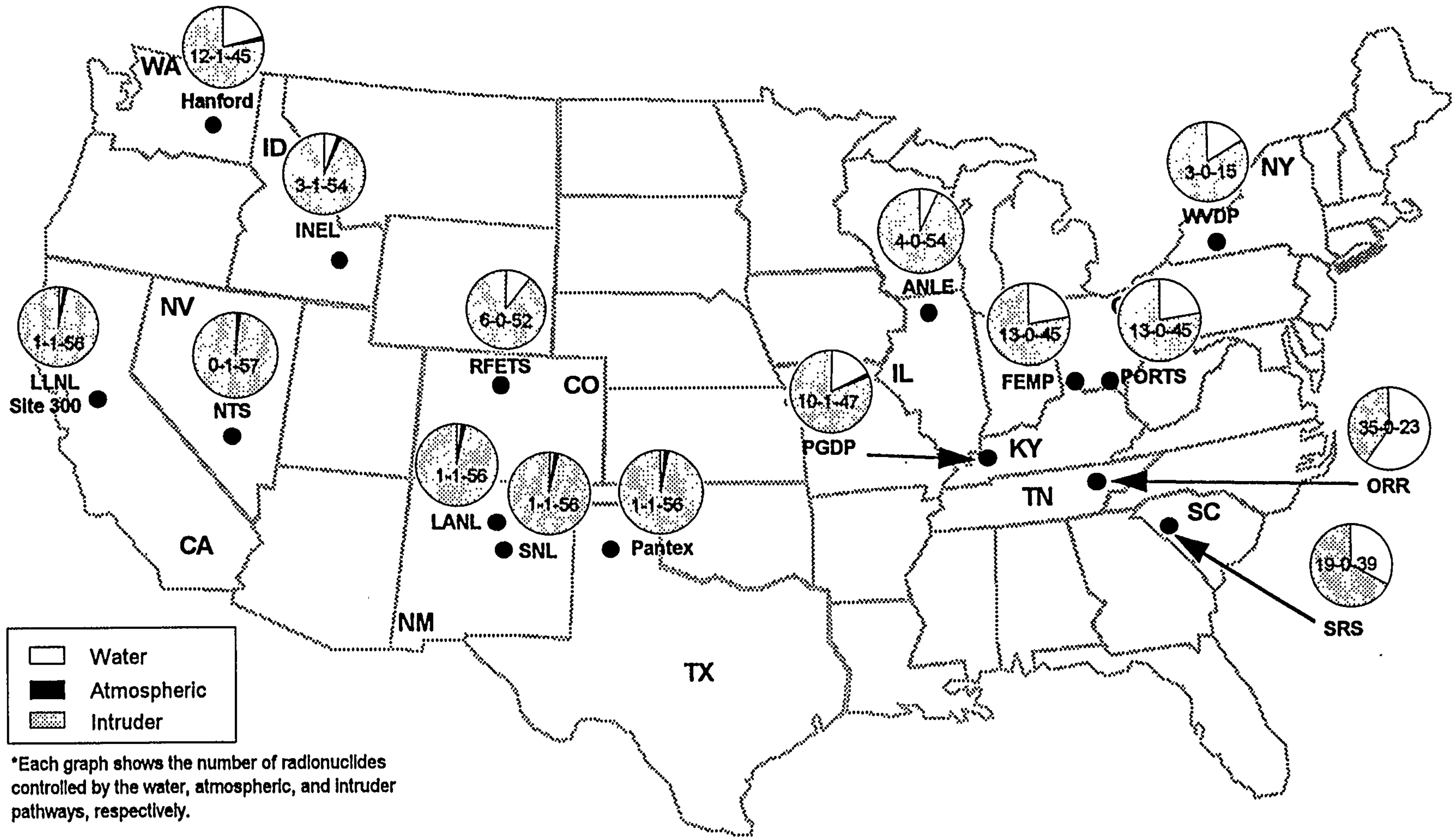


Figure 10. General trend of radionuclides limited by the water, atmospheric, and intruder pathways.

Table 3. Radionuclides Limited by the Water Pathway for the Generic Trench Only (o), for Both the Generic Trench and Tumulus (•), and for the Atmospheric Pathway for Both Facility Types (x)

Nuclide[a]	Arid Sites								Humid Sites							Nuclide
	LLNL	Hanford	NTS[b]	INEL	RFETS	SNL	LANL	Pantex	ANLE	PGDP	FEMP	PORTS	ORR	SRS	WVDP[c]	
H-3		o			o				o	o	o	o	•	•		H-3
C-14	x	x	x	x	•	x	x	x	•	x[d]	•	•	•	•	•	C-14
Si-32														•	-[e]	Si-32
Cl-36		•			•				o	•	•	•	•	•	-	Cl-36
K-40				•	•				o	•	•	•	•	•		K-40
Ni-59												o			-	Ni-59
Se-79		•									o	o	•	•	-	Se-79
Zr-93														•	-	Zr-93
Nb-93m														•	-	Nb-93m
Nb-94													o		-	Nb-94
Tc-99	•	•		•	•	•	•	•	•	•	•	•	•	•	•	Tc-99
Pd-107										o	•	•	•	•	-	Pd-107
Sn-126												o	•		-	Sn-126
I-129		•		•	•				•	•	•	•	•	•	•	I-129
Cs-135		•										o		o	-	Cs-135
Ra-226												o			-	Ra-226
Th-229													•		-	Th-229
Th-230													•		-	Th-230
Th-232													•		-	Th-232
Pa-231		•												•	-	Pa-231
U-232		•									•					U-232
U-233		•								•	•	•	•	•		U-233
U-234		•								•	•	•	•	•		U-234
U-235		•								•	•	•	•	•		U-235
U-236		•								•	•	•	•	•		U-236
U-238		•								•	•	•	•	•		U-238
Np-237					•				•	•	•	•	•	•	-	Np-237
Pu-238												•	•	•		Pu-238
Pu-239													•	o		Pu-239
Pu-240													•	o		Pu-240
Pu-241					o				o				•	o	-	Pu-241
Pu-242													•	o	-	Pu-242
Pu-244													•	o	-	Pu-244
Am-241					o				o			o	•			Am-241
Am-243													•		-	Am-243
Cm-243													•	o	-	Cm-243
Cm-244													•	o	-	Cm-244
Cm-245													•		-	Cm-245
Cm-246													•		-	Cm-246
Cm-247													•		-	Cm-247
Cm-248													•		-	Cm-248
Cf-249													•		-	Cf-249
Cf-250													•		-	Cf-250
Cf-251													•		-	Cf-251

a Fourteen radionuclides not listed--all intruder limited (Al-26, Co-60, Ni-63, Sr-90, Ag-108m, Cd-113m, Sn-121m, Ba-133, Cs-137, Sm-151, Eu-152, Eu-154, Pb-210, and Ra-228).

b No water pathway analysis was performed at this site.

c Only 18 on-site radionuclides were evaluated.

d Trench is limited by the water pathway.

e "-" indicates radionuclide not evaluated at this site

Tritium (H-3) is limited by the water pathway at Hanford, RFETS, and the humid sites (except WVDP) for the generic trench design and at ORR and SRS for both the generic designs. At most sites the generic tumulus design provides sufficient detention for disposal of H-3 at the intruder concentration limit. Tritium is not limited by the atmospheric pathway at any of the sites.

The atmospheric pathway is limiting for C-14 at one humid site, PGDP (generic trench design), and all arid sites except RFETS. The water pathway is limiting for C-14 at the remaining sites for both the generic trench and tumulus designs.

The water pathway is limiting for Tc-99 at all sites but one for both the generic trench and tumulus designs. The exception is NTS, which is assumed to have no water pathway.

Several radionuclides (Cl-36, K-40, Pd-107, I-129, U-233, U-234, U-235, U-236, U-238, and Np-237) are limited by the water pathway at most humid sites for both the generic trench and tumulus designs. These radionuclides are long-lived and relatively mobile in the environment (uranium is mobile only under oxidizing conditions). Several other radionuclides are limited by the water pathway at selected sites.

Fourteen radionuclides not listed in Table 3 (Al-26, Co-60, Ni-63, Sr-90, Ag-108m, Cd-113m, Sn-121m, Ba-133, Cs-137, Sm-151, Eu-152, Eu-154, Pb-210, and Ra-228) are limited by intrusion at all sites. Based on the assumptions used in this analysis, disposal of these radionuclides is possible at all 15 sites at the same permissible waste concentration.

An additional seventeen of the 58 radionuclides (Si-32, Ni-59, Zr-93, Nb-93m, Nb-94, Ra-226, Th-229, Th-230, Th-232, Am-243, Cm-245, Cm-246, Cm-247, Cm-248, Cf-249, Cf-250, and Cf-251) are limited by intrusion at 14 of the 15 sites. The water pathway limits Si-32, Zr-93, and Nb-93m at SRS; Ni-59 and Ra-226 at PORTS; and Nb-94, Am-243 and the radioisotopes of thorium, curium, and californium at ORR. Based on the PE results, the limiting concentrations for disposal of these 17 radionuclides at 14 of the 15 sites are those based on the intruder pathway.

An additional 9 of the 58 radionuclides (Sn-126, Pa-231, U-232, Pu-239, Pu-240, Pu-242, Pu-244, Cm-243, and Cm-244) are limited by intrusion at 13 of the 15 sites. The water pathway limits Sn-126 at PORTS and ORR; Pa-231 at Hanford and SRS; U-232 at Hanford and FEMP; and the radioisotopes of plutonium and curium at ORR and SRS. Thus, the PE results indicate that, in the case of these 9 radionuclides, the permissible waste concentrations are based on the intruder scenarios.

At NTS, 57 of the 58 radionuclides are limited by the intrusion pathway and C-14 is limited by the atmospheric pathway; the water pathway was not evaluated. Because the NTS is the most intrusion limited of the 15 sites, it has the highest overall permissible waste concentrations.

At LLNL, SNL, LANL, and Pantex, 56 of the 58 radionuclides are limited by intrusion, C-14 is limited by the atmospheric pathway, and Tc-99 is limited by the water pathway. The differences in disposal facility performance at these four sites are almost indistinguishable using the PE methodology. The permissible waste concentrations are only slightly lower than at NTS where the water pathway is assumed to be non-existent.

At Hanford, all the uranium isotopes are limited by the water pathway due to their assumed high environmental mobility at that site.

At ORR, 35 of the 58 radionuclides are limited by the water pathway for both the generic trench and tumulus and one additional radionuclide is limited by the water pathway for the generic trench. Based on the assumptions used in this analysis, of the 15 sites, ORR has most restrictive permissible waste concentrations for radioactive waste disposal.

At SRS, 19 of the 58 radionuclides are limited by the water pathway for both the generic trench and tumulus designs and an additional 8 radionuclides are limited by the water pathway for the generic trench design. At FEMP and PORTS, 13 of the 58 radionuclides are limited by the water pathway for both the generic trench and tumulus designs; an additional 2 and 7 radionuclides are limited by the water pathway for the generic trench design at FEMP and PORTS, respectively. At PGDP, 10 of the 58 radionuclides are limited by the water pathway for both the generic trench and tumulus designs and an additional 3 radionuclides are limited by the water pathway for the generic trench design. These results provide an indication of the increased effectiveness of a tumulus facility at these humid sites. Of course, at some of these sites the shallow depth of groundwater precludes subsurface disposal.

4.0 DISCUSSION OF PE RESULTS

The PE is designed as a scoping analysis. Many simplifying assumptions are inherent in the analysis, and the uncertainties associated with certain of the input parameters were generally not taken into account. Despite these limitations, because a consistent analysis was performed at all 15 sites, the PE results provide useful technical information which can assist in making decisions on the disposal of MLLW throughout the DOE complex.

The impacts of the PE conceptual model assumptions and the effects of variations in input parameters on the PE results are described in Chapter 6 of Volume 2, and summarized in Chapter 7 of Volume 2. Simplifying assumptions in the PE which affect the analyses for all pathways and scenarios include the waste form, its long-term behavior, and disposal facility performance. Grouted MLLW is the waste form evaluated in the PE, but the performance of non-grouted waste could readily be substituted into the PE methodology. The assumptions in the PE related to long-term behavior of the wastes in the disposal facility are consistent with the approach used in many LLW performance assessment analyses.

Assumptions about the performance of the engineered barriers in the disposal facilities mainly affect the length of time the waste is assumed to be detained. This primarily affects the permissible waste concentrations for the shorter-lived radionuclides for the water pathway and the intrusion scenarios where, as a result of radioactive decay, longer times of detention result in higher permissible waste concentrations.

Simplifying assumptions related to the water and atmospheric pathway analyses either result in lower permissible waste concentrations or have minor effects on their estimated values. For the intrusion scenario, a change in results for the medium- and long-lived radionuclides of up to three orders of magnitude would occur if only the post-drilling scenario were assumed to apply. Changing the assumed time for the homesteader intrusion scenario to 100 y, the same time as that assumed for the post-drilling scenario, would reduce the permissible concentrations for some of the shorter-lived radionuclides, that would otherwise be limited by the post-drilling scenario, by up to three orders of magnitude. Longer-lived radionuclides are minimally affected by such a change in the times at which intrusion is assumed to occur. However, an assumption of a homesteader scenario at 100 y may not be reasonable if engineered barriers are assumed to maintain their integrity beyond the period of active institutional controls.

A parameter sensitivity analysis was performed to examine whether the effects of variations in input parameters on the resulting permissible waste concentrations could change the limiting pathway (e.g., if intruder scenarios had the lowest permissible waste concentration, what variations in input parameters were required to cause the water pathway to yield the lowest permissible waste concentration?). For radionuclides limited by the water pathway, the permissible waste concentrations were most sensitive to the assumed values of the distribution coefficients for the grouted waste. This parameter has a controlling effect on the radionuclide concentration in the leachate exiting the disposal facility. However, generic values were used for the grout distribution coefficients in the PE, so variations in the coefficient affect all sites in the same manner. For shorter-lived radionuclides at humid sites, their permissible concentrations were also sensitive to values for the natural recharge and the distribution coefficients of the geologic media. Large (often seemingly unreasonable) changes in these parameters, however, were required to change the limiting pathway for most radionuclides at most sites. For these reasons, there is confidence in the limiting pathways as identified by the PE results. The permissible waste concentrations for the atmospheric pathway were relatively insensitive to changes in site-specific parameters due to the relatively generic nature of the analysis.

The PE results were compared with results from site-specific performance assessments at INEL, Hanford, ORR, and SRS. Two other sites, NTS and LANL, are currently preparing LLW performance assessments, but sufficient data were not available to permit comparisons to be made at this time. For the water pathway, the PE results are within two orders of magnitude of the performance-assessment results for all radionuclides and within less than one order of magnitude of the performance-assessment results for most radionuclides at most sites. The closest comparison occurred at INEL, and the poorest comparison occurred at ORR. In all cases the PE results provide more conservative (i.e., lower) permissible waste concentrations than the performance assessments due to the more conservative transport assumptions used in the PE. The differences in water pathway results between the PE and the performance assessment analyses were primarily due to differences in methodologies.

The intruder analyses used in the PE are generally based on the analysis used in the ORR and SRS performance assessments. Except for the case of Am-241 at SRS, the PE results and the results from the ORR and SRS performance assessments compared closely. The PE results for the intruder scenarios also generally show close comparison with the results derived from the performance assessments conducted for INEL and Hanford.

5.0 CONCLUSIONS

Many factors are important in developing and comparing MLLW disposal options, including the selection of the method for treating the waste, the resulting stabilized waste form, the disposal facility design, transportation costs and risks, and related social and political factors. As applied here, the PE is a simple, scoping-level analysis that provides technical information on the capabilities of 15 DOE sites to dispose of 58 radionuclides in generic trench and tumulus facilities. Additionally, these facilities are assumed to satisfy the relevant design requirements of RCRA for the hazardous constituents of the MLLW. The PE provides no conclusions about the policy decisions of where to store or dispose of MLLW.

The 15 sites analyzed in this report are classified as "arid" or "humid" according to their climatological characteristics. The sites classified as arid are LLNL, Hanford, NTS, INEL, RFETS, SNL, LANL, and Pantex. The sites classified as humid are ANLE, PGDP, FEMP, PORTS, ORR, SRS, and WVDP.

- All 15 DOE sites considered in this analysis have the technical capability for disposal of some radioactive materials in mixed low-level waste. This conclusion is based on the concentration limits that were estimated using the pathways for release of radionuclides to water and the atmosphere and the assumed scenarios for inadvertent human intrusion into disposal facilities.

  However, the technical capabilities for disposal of radioactive materials in mixed waste also appear to differ significantly among the sites. Differences of up to four orders of magnitude in the estimated concentration limits have been calculated for some radionuclides at the various sites when the limits are based on the most restrictive of the results for the water and atmospheric pathways and intrusion scenarios at each site. For some radionuclides, even greater differences were seen in the separate results for the water release pathway among the various sites, due primarily to the differences in the assumed water travel times between humid and arid sites. The inadvertent human intrusion scenarios used in the analysis were largely generic and did not distinguish between sites.

- For most radionuclides, the assumed scenarios for inadvertent human intrusion were more important in determining the estimated concentration limits for disposal than the scenarios for release to water or the atmosphere, particularly for sites located in arid regions. The intrusion scenarios considered in this analysis were based on scenarios commonly used in performance assessments for DOE facilities disposing of low-level radioactive waste. The scenarios are largely generic and, thus, the estimated radionuclide concentration limits are the same for nearly all sites.

  The intrusion scenarios considered in this analysis were developed based on the assumption of current human behavior to provide estimates of waste acceptance criteria in the form of concentration limits of radionuclides. Therefore, the issues associated with the recognized inability to predict the social behavior of populations far into the future were avoided.

- Particularly at sites located in humid regions, the estimated concentration limits for disposal of some radionuclides were determined by the analysis for the water pathway. At other sites and for many radionuclides, however, the water pathway was not important because the radionuclide travel time to the performance boundary either was much greater than the half-life of the radionuclide involved or was longer than the 10,000-year time of compliance assumed in the analysis. However, the estimates of permissible radionuclide concentrations in waste based on the peak concentrations, whenever they occur, have been calculated and are presented in the report.

  The modeling of the water pathway in this analysis is believed to be conservative for most sites. Therefore, in cases where a high concentration limit, or no limit, was estimated, a more sophisticated and rigorous analysis of the water pathway may not be warranted, provided performance measures similar to those assumed in this analysis were applied to future disposal facilities. On the other hand, in cases where a relatively low concentration limit for the water pathway was obtained (e.g., at the ORR and SRS sites), more refined and less conservative analyses, which take into account additional site-specific factors relevant to radionuclide transport in water, could be used to obtain more realistic calculated concentration limits for the water pathway based on additional site characterization data. Additionally, as site characterization continues and more information becomes available, additional exposure pathways might be identified, which could result in changes to the concentration limits.

- The analysis for the water pathway clearly demonstrated that engineered barriers offer no significant long-term advantages for the disposal of wastes containing longer-lived radionuclides. The primary advantage of engineered barriers is for the disposal of wastes containing shorter-lived radionuclides.

- The intrusion evaluation demonstrated that the permissible concentrations for medium-lived and longer-lived radionuclides were increased by up to three orders of magnitude at sites where the homesteader scenario was not credible (e.g., where waste was disposed of below grade at a depth sufficient to preclude this type of intrusion). However, a sufficiently thick vadose zone is required, a condition that generally occurs only at the arid sites.

- Through sensitivity analyses, the PE provided insights on key parameters (e.g., natural recharge and groundwater flow rates at a site, half-lives, and mobility of radionuclides) characterizing both the sites and the wastes and revealed the impacts of changes in these parameters on the estimated concentration limits for various radionuclides. The PE also showed that the degree of conservatism in the estimated concentration limits of radionuclides depend on the implicit assumptions in the transport models and scenarios as well as on values assigned to key input parameters.

- Indicator radionuclides were identified as effective surrogates for those radionuclides having similar properties and characteristics. The PE analysis showed that appropriately selected indicator radionuclides can be used in site-specific analyses of disposal facilities, thus reducing the analysis time and cost without resulting in significant additional uncertainties in the analyses.

- The PE methodology was demonstrated as a useful scoping-level tool which provides a readily available approach for identifying important transport and exposure pathways. The PE methodology can also be used to identify where more detailed site-specific water pathway transport analyses may be required to determine more realistic estimates of the concentration limits for specific radionuclides.

The PE methodology does not provide a substitute for the long-term performance assessments required by DOE Order 5820.2A for planned disposal facilities. It is likely that site-specific performance assessments for the water and atmospheric release pathways would differ from the results in the PE analysis; the magnitude of the difference depends primarily on the differences in the assumptions used in the analyses. Site-specific analyses of inadvertent intrusion also may differ from the results of the PE methodology in some cases.

The results of the PE or a site-specific performance assessment will not be the sole basis for decisions about waste disposal at particular DOE sites or within the DOE complex. A variety of additional factors need to be considered including, for example, the results of safety analyses for disposal facility operations, the degree to which a potential disposal site has already been contaminated by past operations or waste disposals, the benefits and costs associated with shipping waste from one site to another, and the issue of having many smaller disposal facilities at a variety of sites compared to having a smaller number of larger facilities at selected sites. Although adequate technical analyses are required for siting waste disposal facilities, economic and social concerns clearly will play an important role in their selection.

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