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BRANCH TECHNICAL POSITION ON

PERFORMANCE ASSESSMENT FOR
LOW-LEVEL WASTE DISPOSAL FACILITIES

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Low-Level Waste Management Branch
Division of Low-Level Waste Management & Decommissioning
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A. INTRODUCTION

A.1 Objective of the Branch Technical Position

The U.S. Code of Federal Regulations, Title 10, Chapter 1, Part 61 "-- Licensing Requirements for Land Disposal of Radioactive Waste," (Part 61) specifies license requirements and performance objectives for low-level radioactive waste (LLW) disposal facilities with the goal of protecting public health and safety and the environment. The Part 61, Subpart C, Performance Objectives govern: (1) protection of the general population from releases of radioactivity off-site, (2) protection of inadvertent intruders, (3) protection of individuals during facility operations, and (4) stability of the disposal site after closure. An LLW performance assessment is an essential component of the licensing process to provide reasonable assurance that the performance objectives will be met. Performance assessment is specifically concerned with analyses of the post-closure performance of an LLW disposal facility.

The guidance objective of the "Branch Technical Position on Low-Level Radioactive Waste Performance Assessment" is to provide license applicants, licensees, States and compacts, and U.S. Nuclear Regulatory Commission staff with an acceptable strategy and methodology for performing the technical analysis required to demonstrate compliance, in the post-closure timeframe, with the performance objective, in Part 61, governing radiological protection of the general public (§ 61.41). This includes giving: (1) general guidance on an acceptable performance assessment strategy that integrates site characterization and performance assessment modeling; and (2) specific guidance on implementing NRC's performance assessment methodology (PAM). The PAM was developed by NRC staff as one approach that may be followed in conducting a performance assessment for an LLW disposal facility. The technical position will augment the guidance pertaining to LLW performance assessment currently contained in the "Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility" (NRC, 1991a, NUREG-1200), and the Standard Format and Content Guide, (NRC, 1991b, NUREG-1199). The guidance presented in this technical position is not a regulatory requirement and acceptable demonstrations of compliance with Part 61 provisions may be developed by other methods.

This technical position on LLW performance assessment, however, is not intended to address all the issues in a complete safety analysis report (SAR) that is required for an LLW disposal facility license application (as recommended in NUREG-1199). For example, operational performance issues and technical analyses to address them are not dealt with here, unless particular aspects of the facility operations will have an impact on the long-term performance of the facility. In addition, issues relating to site characterization, and the design and construction of a facility are not discussed, except as they relate to assessing the post-closure performance of the disposal site.

A.2 Regulatory Requirements for Performance Assessment

Performance Assessment is focused on disposal site performance during the post-closure timeframe. The objective of a performance assessment is to demonstrate compliance with

§ 61.41, "Protection of the General Population from Releases of Radioactivity," which requires that:

> "Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable."

The specific technical analyses required to demonstrate compliance with § 61.41 are contained in §§ 61.13(a), which enumerates three requirements:

> (1) that "Pathways analyzed in demonstrating protection of the general population from releases of radioactivity must include air, soil, ground water, surface water, plant uptake and exhumation by burrowing animals";
>
> (2) that "The analyses must clearly identify and differentiate between the roles performed by the natural disposal site characteristics and design features in isolating and segregating the wastes"; and
>
> (3) that "The analysis must clearly demonstrate that there is reasonable assurance that the exposure to humans from the release of radioactivity will not exceed the limits set forth in § 61.41."

Paragraph 61.50 (a)(2) states that "The disposal site shall be capable of being characterized, modeled, analyzed, and monitored." The specific intent of this requirement is to provide a criterion for site suitability that is aimed at minimizing the complexity of the site and the associated uncertainty in the technical analyses of site safety, including performance assessment.

The performance assessment approach described in this technical position is not intended to address radiation safety issues related to demonstrating compliance with Part 61 performance objectives governing protection of inadvertent intruders (§ 61.42); protection of individuals during operations (§ 61.43); and stability of the disposal site after closure (§ 61.44).

Operational practices, emergency responses to accidents, and monitoring programs, as described in the radiation safety program for control and monitoring of potential operational releases, should provide assurance that individuals on and off-site are protected from routine operations and from accidents that may occur during both the operational and the site closure periods when waste handling, storage, and disposal activities are occurring. Monitoring programs, including action levels proposed by the applicant, will provide early warning of radionuclide releases from the disposal facility, before they leave the site boundary. If necessary, operational procedures may be modified or other mitigating actions taken to ensure that operational releases of radioactivity are maintained within the individual dose requirements of § 61.41 that are incorporated by reference in § 61.43.

Separate intruder scenario dose analyses are not usually required in a performance assessment. Rather, §§ 61.13(b) requires that "Analyses of the protection of individuals from inadvertent intrusion must include demonstration that there is reasonable assurance the waste classification and segregation requirements will be met and that adequate barriers to inadvertent intrusion will be provided." However, an intruder scenario analysis may be required if the projected waste spectra are fundamentally different from those considered in the technical analyses done for the "Draft Environmental Impact Statement [DEIS] on 10 CFR Part 61," NUREG-0782 (NRC, 1981). For example, an intruder analysis might be required if the waste proposed for disposal contains anomalously large quantities and concentrations of long-lived radionuclides (e.g., uranium or thorium) such that the intruder cannot reasonably be protected by the waste classification and intruder barrier requirements of Part 61.

Analysis of disposal site stability after closure, as required by §§ 61.13(d), to demonstrate compliance with § 61.44, relates to "... the long-term stability of the disposal site and the need for ongoing active maintenance after closure...." Many of the factors affecting long-term stability, such as siting, waste form and emplacement, and design and construction features also are factors affecting the release of radionuclides off-site that need to be considered in performance assessment analyses. However, stability analyses are typically dealt with in the site characterization, facility design and construction, and closure sections of the regulations and the SAR.

B. BACKGROUND

B.1 Need for Low-Level Waste Performance Assessment Guidance

The Low-Level Waste Policy Act of 1980, and the Low-Level Waste Policy Amendments Act of 1985 establish State responsibility for disposal capacity of commercially generated LLW [see NUREG-0980, (NRC, 1991c)]. Licensing of new facilities is a responsibility of either the NRC, under Part 61, or Agreement States, under comparable disposal regulations. Improved performance assessment guidance will assist regulatory authorities in carrying out their responsibilities by providing license applicants with: (1) an acceptable overall approach to performance assessment modeling, and (2) acceptable means of resolving specific technical modeling issues. Another guidance need is to supplement existing general guidance so as to provide a linkage between overall data and design requirements and specific performance assessment needs.

A range of land disposal technologies can be applied in the disposal of LLW, including shallow-land burial, below-ground vaults (BGVs), earth-mounded concrete bunkers (EMCBs), above-ground vaults with no earthen covers (AGVs), mined cavities, and augured holes. Traditionally, all commercially generated LLW has been disposed of near-surface, by shallow land burial that has relied on relatively simple designs to isolate wastes from infiltrating water, and on natural site characteristics to attenuate any potential releases that might occur. Shallow land burial LLW facilities at Barnwell, South Carolina, and Richland, Washington, are currently operational. Many of the designs being considered by applicants for future LLW facilities focus on engineering enhancements, such as concrete vaults and multi-layered covers, to help isolate waste from the accessible environment. Therefore, guidance is needed, not only on how to model and analyze natural systems, but also on engineered barriers and how much reliance can be placed on engineering enhancements in demonstrating that performance objectives are met. The guidance presented in this technical position is intended to be generally applicable to any method of land disposal; however, only technical issues that specifically are attributable to the performance of near-surface disposal technologies are addressed. Performance issues related to land disposal in AGVs or disposal deeper than 30 meters (mined cavities and augured holes) will need to be evaluated and addressed separately.

Based on State and NRC staff experience, several additional areas have been identified where further guidance for performance assessment is required, including:

(1) an overall understanding of the performance assessment process;
(2) the relationship between site characterization and performance assessment data collection;
(3) modeling of infiltration rates, source term releases, and concrete and engineered barrier degradation;
(4) transport of radionuclides in the environment;
(5) verification and validation of computer models;
(6) the use of generic data in performance assessment; and
(7) uncertainty and sensitivity analyses.

NRC documents currently provide some guidance about LLW performance assessment-related issues. These include: the Standard Format and Content Guide, NUREG-1199; the Standard Review Plan, NUREG-1200; and the Environmental Standard Review Plan, NUREG-1300. NUREG-1200 provides guidance applicable to evaluating a performance assessment and presents the process that would be used by NRC staff in reviewing a license application. NUREG-1199 details the necessary components of a license application for an LLW disposal facility required under Part 61. In both documents, Chapter 6, "Safety Assessment," deals with the technical analyses required to demonstrate compliance with Part 61 performance objectives. Section 6.1, "Release of Radioactivity" (Sub-Sections 6.1.1 - 6.1.5.4) specifically deals with meeting § 61.41 and is primarily concerned with performance assessment. However, it provides only general guidance on LLW performance assessment and does not address many specific issues or recommend means for resolving them. Therefore, NRC staff has prepared this technical position to assist in filling that need to provide guidance in the performance assessment area. Information necessary for meeting the Part 61 siting and facility design requirements are described in Chapters 2, "Site Characteristics," and Chapters 3, "Design and Construction," of NUREG-1199 and NUREG-1200. These chapters identify information needed for a license application. However, not all the site and design data identified in NUREGs 1199 and 1200 would necessarily be used in a performance assessment and may be identified for other purposes, such as site monitoring, and for demonstrating operational safety and stability in design. One of the goals of this technical position is to provide a linkage between overall data and design requirements and specific performance assessment needs, which may not be directly apparent in NUREG-1199 and NUREG-1200.

B.2 Overview of Performance Assessment

B.2.1 Development of Performance Assessment Process

NRC staff formulated a general performance assessment strategy in 1987, that presented a modular approach to LLW facility systems modeling (Starmer, et al., 1988). The modular approach being suggested by NRC staff for conducting a performance assessment is set out in Figure 1 In the modular approach, disposal system modeling is logically divided into discrete modules: (1) infiltration and unsaturated zone flow; (2) engineered barrier performance (coupled with infiltration analysis to calculate the water flux into disposal units); (3) radionuclide releases from waste forms and the bottoms of disposal units (container failure, leaching, and near-field transport); (4) ground water, surface water, and air pathways; (5) plant and animal uptake (food chain); and (6) human dose. The modular approach allows a mix of both complex and simple models to be used in the overall performance assessment. The appropriate degree of modeling complexity within a module is determined by the availability of suitable data and the associated data uncertainty. Generally, complex models require more abundant and detailed data than less sophisticated models, which rely more on simplifying assumptions and generalized data that are supported by site data, as needed. The approach involves the development of simplified and reasonably conservative conceptual models and analyses that capture the critical interactions of the release and transport processes given site-specific conditions, engineered design, radionuclide releases (source term), and human exposure scenarios.

The PAM was developed for NRC at Sandia National Laboratories (SNL) to assemble models and codes acceptable for analyzing the various disposal system modules set out in the NRC staff performance assessment strategy. The PAM was produced in five steps: (1) identifying potential human exposure pathways; (2) assessing the relative significance of exposure pathways; (3) selecting and integrating models; (4) identifying and recommending computer codes; and (5) implementing and assessing computer codes (Shipers, 1989; Shipers and Harlan, 1989; Kozak, et al., 1989a,b; and Kozak, et al., 1990a,b). In identifying and assessing appropriate sub-models for performance assessment, SNL noted significant sources of uncertainty existed for analyzing several important areas, including infiltration through covers, engineered barrier degradation, and radionuclide leaching. A summary of the technical issues in LLW performance assessment is presented in Section B.2.3. In recognition of the problems in these technically difficult modeling areas and other issues (see Section B.1), the NRC continues to support work on enhancing staff LLW performance assessment capability. This ongoing effort has provided the staff with new insights that are reflected in the resolutions to the technical policy issues presented in Section D and the technical approaches described in Section E of this technical position.

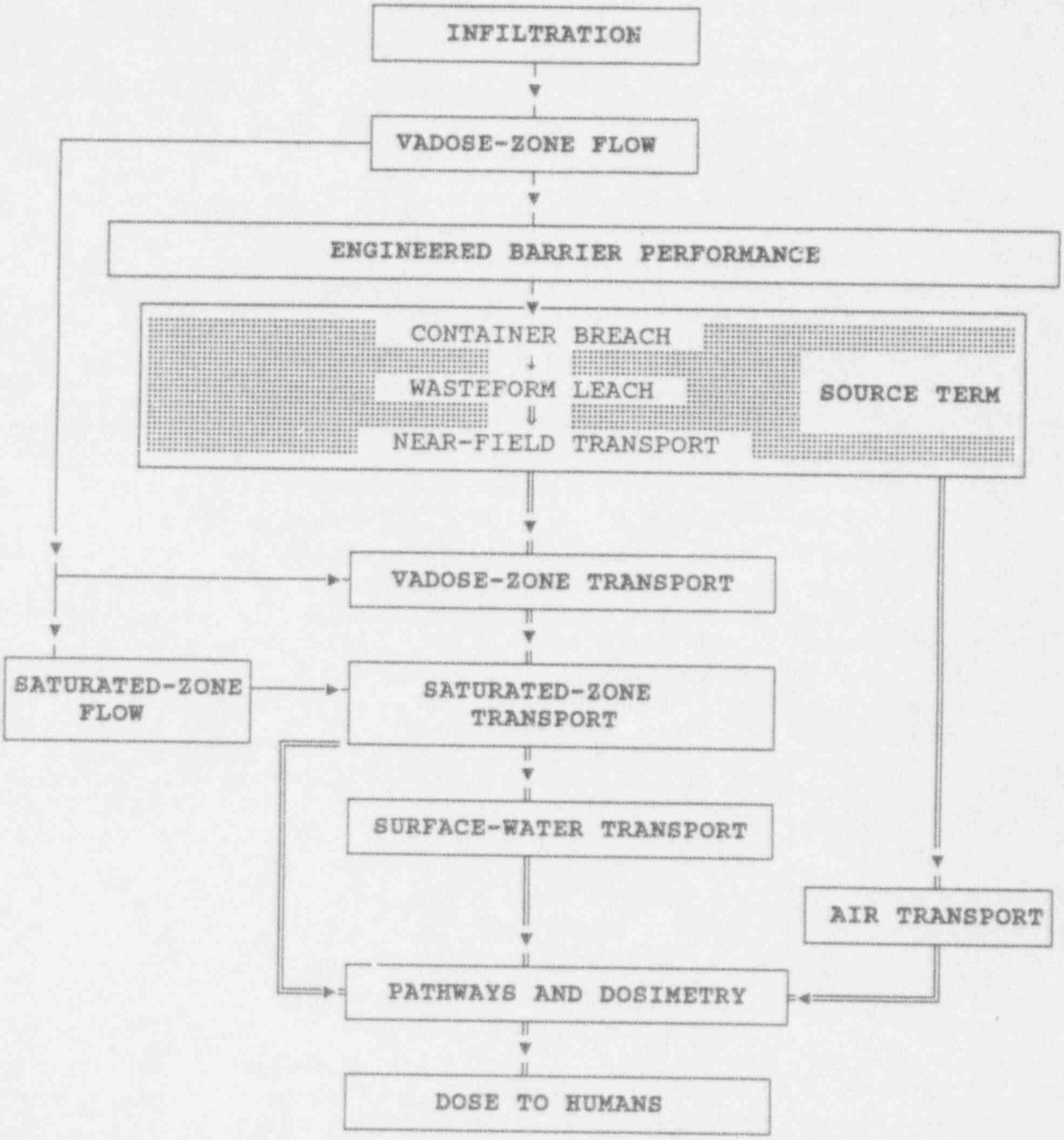


Figure 1. Modular conceptual model of processes in low-level waste performance assessment (modified from Kozak, et al., 1990b).

[Note: Single lines correspond to water flow pathways, double lines correspond to radionuclide transport pathways, and the stippled region corresponds to the disposal cell(s)].

Although specific models and codes may be discussed in various sections of this technical position, or within particular references cited, NRC does not endorse the use of specific models and codes for performance assessment. It is essential for the applicant to establish a rigorous quality assurance program at the beginning of the performance assessment process and to provide proper and appropriate justification, documentation, and verification of any models or codes used in the analysis.

Finally, since developing the PAM, the NRC staff has continued to develop its LLW performance assessment program, which has included interactions with Agreement States on site-specific performance assessment issues, other NRC LLW-related reviews, NRC research and technical assistance contractor studies, NRC staff performance assessment modeling studies, and participation in an International Atomic Energy Agency program on performance assessment of LLW sites and the international cooperative project on geosphere model validation, the INTRAVAL Project. From this experience has evolved the overall performance assessment process presented in Section C of this technical position. The process unites performance assessment modeling with related elements of site selection, site characterization, and facility design to identify site information most essential for demonstrating regulatory compliance.

B.2.2 Post-closure Performance LLW Disposal Systems

A land disposal facility is the land, buildings, and equipment that are necessary to carry out the disposal of LLW. A disposal site is that portion of a land disposal facility that is used for the disposal of waste. It consists of a number of disposal units surrounded by a buffer zone. A disposal unit is a discrete portion of the disposal site into which waste is placed for disposal. Disposal units may range from earthen trenches to concrete vaults. A buffer zone is a portion of the disposal site that is controlled by the licensee and that lies under the site and between the disposal units and any disposal site boundary. The buffer zone provides controlled space to establish monitoring locations that are intended to provide an early warning of radionuclide movement.

Engineered barriers are man-made structures or devices that are intended to improve or enhance the natural site's ability to isolate and contain waste, and to minimize possible release of radionuclides to the environment. An example of an engineered barrier system is shown in Figure 2. The engineered system depicted consists of various sub-system components, including: (1) the waste forms and containers; (2) the disposal vaults; (3) the back-fill material; (4) vault drainage systems; (5) interior moisture barriers and low permeability membranes; and (6) a layered earthen cover. These components of the engineered system operate in conjunction with the characteristics of the natural site, to form an integrated waste disposal system, to ensure protection of the public health and safety, and the environment.

The cover provides protection by minimizing infiltration of water into waste disposal units [§§ 61.51(a)(4)] and also provides shielding from direct gamma exposure [§§ 61.52(a)(6)]. Covers may range from simple earthen caps to complex multi-layer engineered systems (e.g., with drainage layers, capillary breaks, and moisture wicks) to prevent any significant

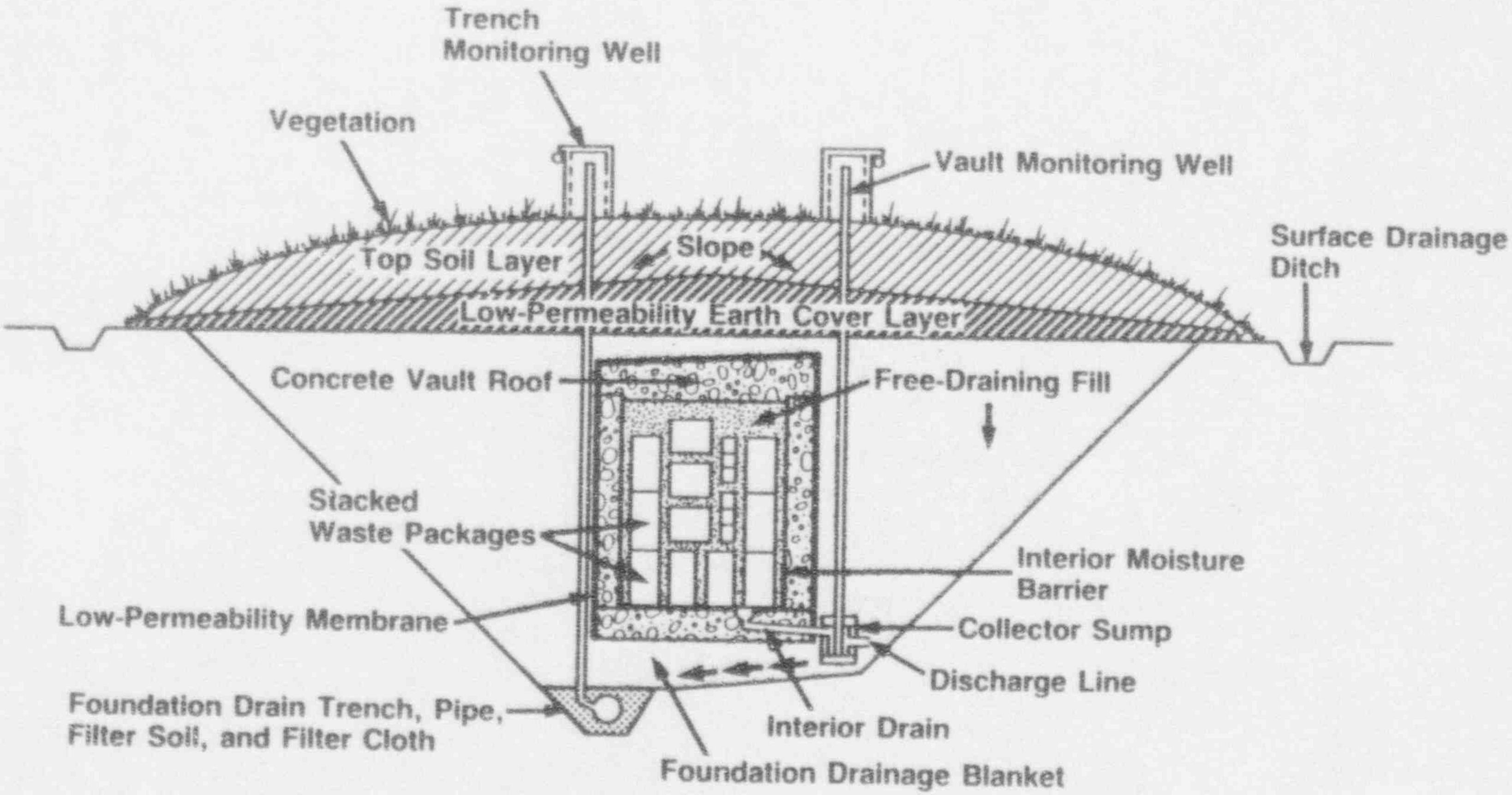


Figure 2. Example of LLW disposal engineered barrier system.

quantities of water from contacting the waste during the design life of the cover (see Cartwright, et al., 1987; Schulz, et al., 1988 and 1992; Smyth, et al., 1990; Bennett, 1991; Bennett and Horz, 1991; and Bennett and Kimbrell, 1991). Performance of disposal unit covers is dependent on site stability. Technical requirements for waste segregation, waste form, design, and site suitability are intended to promote cover stability and minimize access of water to the waste.

Many of the disposal unit designs being proposed by States and Compacts focus on engineered structures (i.e., concrete vaults and complex covers) to help isolate waste from the accessible environment. Concrete vault systems may include: (1) BGVs; (2) EMCBs (i.e., above-grade, but covered with earthen material); (3) AGVs; or (4) shaft disposal (SD) (see Bennett, et al., 1984; Warriner and Bennett, 1985; Bennett and Warriner, 1985; Miller and Bennett, 1985; Bennett, 1985; and Denson, et al., 1987 and 1988).

The natural site consists of (1) the hydrosphere and geosphere (i.e., the geologic and hydrogeologic systems, including surface water); (2) the surrounding atmosphere; and (3) the biosphere. Natural characteristics of an LLW disposal site should promote disposal site stability and preclude or attenuate the transport of radionuclides away from the disposal site into the general environment. Although engineered barriers can be used to improve or enhance disposal site performance, the natural setting must be relied on for safety. The minimum characteristics that a disposal site must have to be acceptable for near surface disposal of LLW are identified in the technical requirements of § 61.50. Sites generally must exhibit the following characteristics: (1) a geology that is relatively simple; (2) well drained soils that are free from frequent ponding or flooding; (3) not susceptible to surface geological processes such as mass wasting, erosion, slumping, landsliding, and weathering, which may occur with such frequency or extent to significantly affect the ability of the disposal site to meet the performance objectives; (4) sufficient depth to the water table so that ground water will not periodically intrude into the waste or discharge on site; (5) not susceptible to tectonic processes such as folding, seismic activity, and volcanism, which may occur with such frequency or extent to significantly affect the ability of the disposal site to meet the performance objectives; (6) no known potentially exploitable natural resources; (7) limited future population growth or development; and (8) not adversely impacted by nearby facilities or activities.

Releases of radionuclides that may occur during routine performance of an LLW disposal site result from a number of physical and chemical processes. A portion of the precipitation that impinges on the engineered cover passes through the cover into the disposal units. Since water is the primary solvent for mobilizing radionuclides from the waste, container degradation and waste form leaching generally must occur before significant radionuclide releases from the facility develop. (Note that small amounts of gas may exist in the waste [e.g., ^{85}Kr] or be generated in the absence of water [e.g., ^{222}Rn], but generation of large amounts of ^{14}C and ^{3}H containing gaseous species [e.g., $^{14}CO_2$, $^{14}CH_4$, etc.] generally occurs in the presence of infiltrating water.) Backfill material is placed around the waste containers, to provide stability to the cover system, in accordance with §§ 61.52(a)(5). Backfill may also be used to provide an additional line of defense against release, if it is engineered to have specific chemical and physical properties that enhance retention of radionuclides. The radionuclide flux leaving the disposal units is called the "source term."

Ground water is potentially the most important transport media from a sub-surface disposal facility. This is because that infiltration of water into the disposal units, container degradation, radionuclide mobilization, and transport from the facility are controlled by the surrounding ground-water flow system. Transfer to ground water occurs as radionuclides exiting disposal units are convected and dispersed in water moving in the unsaturated and saturated zones beneath the site. The most important exposure pathways linked to the ground-water medium include both drinking and irrigation from a well. Transport of ground-water contaminants to surface water via seepage and springs and subsequent exposure through various pathways is usually considered of secondary importance relative to the direct ground-water route, because of the additional dilution that occurs in surface water systems. However, for AGVs with no earthen cover, direct surface runoff can be a significant transport route, particularly in humid regions, because of the degradation of the facility by surficial processes. Likewise, air transport must also be considered in a performance assessment. Although it is generally of secondary importance relative to ground water and surface water and associated exposure pathways, air transport and associated exposure pathways may be significant for particular designs [e.g., AGVs with no earthen cover (Kozak, et al., 1993)], or for certain regions (e.g., arid sites), or if specific chemical and physical conditions might occur in the facility such that gas generation may control the potential release of certain radionuclides (e.g., ^{14}C and ^{3}H).

Radiation doses to humans from radionuclides transported through environmental media are directly proportional to the time-dependent concentration of radionuclides at human access locations. Exposure to radiation at human access locations occurs through internal and external dose pathways. Internal doses result from radionuclides being incorporated into the body primarily through inhalation of contaminated air and the ingestion of contaminated food and water. External doses occur from direct radiation sources outside the body, such as contaminated surfaces and air. The sum of the doses from all of the radionuclides in all significant exposure pathways is the dose to the maximally exposed individual. The maximally exposed individual is assumed to reside at the site boundary where doses from most off-site exposure pathways are expected to be greatest.

B.2.3 Technical Issues in Performance Assessment

In modeling LLW disposal systems, there are key technical concerns that are the cause of much of the data and model uncertainty in performance assessment. These concerns must either be modeled directly, or in some way accounted for in assessing disposal site performance.

The purpose of modeling infiltration is to calculate the flux of water into the disposal units. Several important technical areas need to be considered in such an analysis, including: (1) transient surficial processes (e.g., precipitation); (2) changes in site conditions through time (e.g., climatic variability); (3) changes in the performance of the engineered system over time (e.g., degradation of the cover); and (4) how to handle uncertainty in the analysis.

Current knowledge about the long-term durability of materials limits the ability to assess and predict how engineered barriers will perform over long periods of time. Thus, the degree of credit that can be assumed for them in a performance assessment is also limited. The primary concern related to the long-term degradation of engineered barriers is the effect such degradation will have on the flux of water through the engineered system over time. The main issues that will need to be addressed in this area include: (1) the role of engineering judgement and degree of conservatism in performance assessment; (2) predicting long-term performance of materials and engineered elements; (3) consideration of variations in weather patterns in performance assessment; and (4) field verification of (a) engineered material design properties and (b) impact of material heterogeneity on performance of engineered elements.

The performance of waste forms and containers are evaluated as part of the source term. The main focus of the source term modeling area is to calculate the possible flux of radionuclides from the waste forms and containers in the disposal units to the surrounding environment. Source term issues that should be addressed include: (1) developing both screening methods and a general approach; (2) generating an inventory by waste class (A, B, & C), waste streams and waste form; (3) determining credit for container lifetimes (especially for high integrity containers (HICs) for B/C waste); and (4) identifying wasteform specific release mechanisms; and (5) ascertaining chemical considerations that can be included in the source term modeling (e.g., solubility limits).

Identification of the most important environmental transport media and exposure pathways is a fundamental issue in performance assessment modeling that must be done for each individual disposal site. Principal transport media that are likely to be significant at an LLW disposal site include ground water, surface water, air, and biota.

Technical issues that need to be addressed for ground water include: (1) evaluation of site data and analysis from site characterization and identification of ground-water transport pathways; (2) selection of ground-water flow and transport modeling approach; (3) estimation of model input parameters and identification of initial and boundary conditions; (4) calculation of transport to the accessible environment; (5) determination of radionuclide concentrations at receptor locations (e.g., wells, springs, and surface-water bodies); and (6) assessment of uncertainties because of input parameter estimation and ground-water modeling assumptions.

Similarly, for the surface-water system, the major technical issues that need to be addressed include: (1) evaluation of watershed data and site conditions for identifying surface-water transport pathways, including: (a) the ground-water-surface-water linkage, and/or (b) direct surface discharge from the facility; (2) selection of surface water modeling approach (e.g., a stream reach or a watershed model, and assumptions regarding dilution, dispersion, and sediment uptake); (3) determination of channel hydraulic parameters for transport analysis (e.g., velocity field and flow geometries); (4) calculation of radionuclide concentrations at receptor locations; (5) assessment of uncertainties because of input parameter estimation and modeling assumptions.

Technical issues for the air pathway analyses include: (1) identification of release scenarios (e.g., steady-state vs. transient releases and distributed vs. point releases) and associated exposure pathways; (2) selection of air transport modeling approach (including screening methods); (3) estimation of model input parameters and identification of initial and boundary conditions (e.g., wind direction, topography, and stability class); (4) calculation of transport to the accessible environment; (5) determination of radionuclide concentrations at receptor locations; (6) assessment of uncertainties because of input parameter estimation and modeling assumptions.

The biosphere includes natural plants and animals, cultivated crops, and livestock. It is important for two reasons: (1) it provides an exposure path to humans through the consumption of contaminated foodstuffs; and (2) succession of vegetation at the site may have an impact on the design life of the engineered features, such as the cover. Calculation of possible exposure of humans should be dealt with by considering the maximally exposed individual, who is assumed to reside at the disposal site boundary and whose activities include living in a household, drinking water from a well, and consuming foodstuffs from gardening and animal husbandry at the homestead. Other scenarios, involving drinking surface water and consuming foodstuffs obtained from it, must also be considered if these could be a significant pathway (i.e., five percent or more of total dose exposure, as stated in NUREG-1200, page 6.1.3-2).

C. LOW-LEVEL WASTE PERFORMANCE-ASSESSMENT PROCESS

C.1 Overview

The guidance below provides an acceptable overall approach for conducting a performance assessment. The performance assessment process aims to build defensible assessments essential to making a regulatory decision about disposal site performance. In this and subsequent sections, a decision making framework is described that is integrated with aspects of site characterization and facility development that have heretofore been considered separate activities from performance assessment. The performance assessment process outlined in this guidance document was developed by the NRC staff, based on information from numerous sources including: NRC contractor methodologies and models (Kozak, et al., 1990b and 1993); NRC staff LLW-related reviews and experiences; Agreement State LLW-related reviews and experiences; existing LLW literature and data, and NRC staff performance assessment modeling studies.

The above work and experiences yielded several important conclusions about performance assessment modeling that the NRC staff considered before drafting the performance assessment approach presented in this technical position. One conclusion is that performance assessment models that are based on conservative representations of a real disposal system should be adequate for the purpose of making regulatory decisions about site safety. As a site-specific tool for estimating future radiological doses to hypothetical individuals, performance assessment stands in contrast to dose reconstruction modeling, where the goal is to accurately predict doses received by humans from an actual past event or activity.

Because of the complexities and uncertainties inherent in analyzing the behavior of natural and engineered systems over time, simplifying assumptions must be made to address uncertainty about specific disposal facility features and phenomena. Therefore, no performance assessment model can reasonably be expected to be an exact representation of an actual disposal system or provide a precise prediction of dose over either short or long timeframes. However, these uncertainties do not preclude applicants, regulators, or others from making decisions about site safety, as long as uncertainty in the performance assessment is accounted for by an appropriate level of conservatism. Formal validation exercises such as model calibration, history matching, and prediction are inappropriate for performance assessment. What is important, however, is an adequate demonstration that the models perform as they are designed to, and that they conservatively capture the features and processes of the disposal system being modeled.

Another conclusion is that performance assessment is a fundamental element of conducting site selection, facility design, and most importantly, site characterization. As part of the site selection process, simple conservative performance assessment modeling can contribute to a rational selection process and enhance the chances of selecting a suitable site. In designing an LLW facility, performance assessment can provide insights into how to optimize disposal facility design, with respect to a particular site, to achieve acceptable levels of performance for the overall system. Most importantly, because site characterization provides the information used in performance assessment modeling, performance assessment activities require integration with the site characterization program. When conducted as a single integrated process, adequate data and information are amassed to support and defend performance assessment modeling assumptions, model selection, model input data, appropriateness of the performance assessment models to the site, and the treatment of uncertainties with respect to the site.

Initially, performance assessment should provide a number of issues and data needs that must be factored into the site characterization program. As site information is collected, the performance assessment analyst should re-evaluate the modeling assumptions, conceptual models, and data needs, and revise the site characterization program accordingly, to obtain data identified as most needed to reduce uncertainty and establish defensibility of performance assessment results. The site-specific nature of performance assessment will dictate the type and amount of feedback between performance assessment and site characterization. Uncertainty is reduced as successive iterations of data collection and performance assessment are conducted, until adequate confidence in post-closure performance is achieved. If, however, confidence in disposal site performance cannot be achieved, given that very extensive and expensive site characterization is likely to be required to continue the process, the developer may decide to consider another site. This is a practical implementation of the §§ 61.50 (a)(2) requirement that "The disposal site be capable of being characterized, modeled, analyzed and monitored."

It may be desirable to make the site characterization-performance assessment process participatory, where interested parties would have the opportunity to participate in developing and refuting conceptual models as the disposal site is being characterized and evaluated. An open process is expected to improve the technical breadth and defensibility of performance assessments, and eliminate the perception of applicant bias toward more optimistic results. Programs involved with the validation of hydrologic models using laboratory and field data sets have strongly recommended iterative approaches to data collection and modeling or data analysis (INTRAVAL, 1993).

A third staff conclusion is that to account for possible increases in waste inventories from those initially considered, performance assessment should be used to establish site-specific inventory limits for certain radionuclides, to ensure long-term safety of the facility. Radionuclides of concern include long-lived radionuclides such as ^{129}I, ^{99}Tc, ^{14}C, ^{36}Cl, and Th, U, and their daughter products. The concept of site and facility specific inventory limits is incorporated into §§ 61.7(b)(2) and was considered fundamental for ground-water protection in the supporting analysis in the DEIS and Final Environmental Impact Statement (FEIS) for Part 61 (NRC, 1981 and 1982). However, due to the extremely site specific nature of ground-water migration and potential impacts, which are a function of the total inventory of particular radionuclides at the disposal facility, NRC did not develop generic inventory or concentration limits as a part of development of the Part 61 regulation. Rather, each disposal facility must be analyzed on a case-by-case basis and, depending on the specific environmental conditions of the disposal facility, as well as the particular design of the disposal facility, a maximum site inventory of certain radionuclides may be required for the particular site.

Finally, the staff concludes that deciding whether a site meets the performance objective (§ 61.41) should be based on formal quantitative analyses of uncertainty and sensitivity, where for each conceptual model considered in the performance assessment, parameter variations are expressed in a distribution of calculated doses. The uncertainty analysis should be performed over the broadest range of conceptual models, assumptions, potentially adverse conditions, and parameters that cannot be refuted by site information and data. Generally, before an uncertainty analysis can lead to a favorable regulatory finding, a number of data collection and assessment iterations will need to be undertaken to narrow the range of possible conceptual models and/or parameter distributions, to reduce uncertainty. Confidence in the performance assessment results is intrinsically built into the process, because the reasons for modifying initially simple and generally more conservative assumptions, models, and conditions are well-documented and supported by data obtained through successive site investigations and assessments aimed at reducing uncertainty.

C.2 Executing the Performance Assessment Process

The performance assessment process described below, in Steps 1 to 9, should be integrated with site characterization activities that are directed toward evaluating compliance of a disposal facility with the performance objectives in § 61.41. In the discussion to follow, it should be understood that the approach to site characterization undertaken for monitoring or other activities such as design is outside the scope of this discussion. A flowchart of the overall performance assessment process is shown in Figure 3.

1. Initial Data Evaluation: performance assessment begins with an evaluation of available site data, preliminary facility design, and inventory information, to develop

a basic knowledge base about the site and facility. Use of generic as well as site-specific and regional information may be appropriate at this stage of the process. Preliminary assessments done with this basic data may be used in site characterization and facility design activities for the express purpose of evaluating the adequacy of existing information and directing further data collection efforts towards more specific and detailed information necessary to demonstrate compliance. It is important to note that there is always some performance-assessment-relevant information available about all parts of the United States. For instance, geological maps, regional hydrology, and weather data are generally available and in many cases more detailed information may also be available from other engineering projects. NUREG-1199 contains detailed guidance on basic data needs, suggested sources for published and unpublished reports, and records of specific information on natural site characteristics.

2. Initial Conceptual Models and Parameter Distributions: The initially available basic information should next be used to develop assumptions about the behavior of the disposal site (i.e., engineered and natural features) and to develop site-specific conceptual models. At this stage of the process, it may be appropriate to make subjective judgements about the behavior of the site, based on the availability of "soft" data about the site, past experience with similar sites, precedent, and professional judgement. However, assumptions and conceptual models should be as broad as possible, within the constraints of the available information, to reflect the level of uncertainty in the behavior of the system. This means that when only sparse or generic data are available, conceptual models would include more conservative conditions than would be the case when more site-specific information is available. However, it is typically not possible to identify the relative conservatism of conceptual models or parameter sets before the analysis is run. Therefore, conservatism among analyses must be identified after the analyses are performed.

   Parameter distributions for each conceptual model should also be established at this point. As in the development of conceptual models, the goal at this stage is to assume the broadest ranges possible within the limits of available information. If no site-specific data are available for a particular parameter, the range can be set, based on maximum and minimum values that are physically possible or that have ever been measured for similar conditions. These extremes would be modified, to reflect site-specific data, as the site characterization and design process progresses, and more information is collected. If the applicant uses a broad range for a particular parameter and finds that it does not influence the regulatory decision, the applicant may not need to expend additional effort in studying that parameter further.

   Uncertainties, especially in the early stages of site characterization, are likely to result in multiple disposal site conceptual models, and broad distributions of model input parameters. The structure of this uncertainty is depicted in Figure 4, where in this case, the analyst or applicant has generated four alternative conceptual models, each with different parameterizations. It should be noted that the division between different conceptual models and different parameter distributions for the same model may be artificial and not always clear.

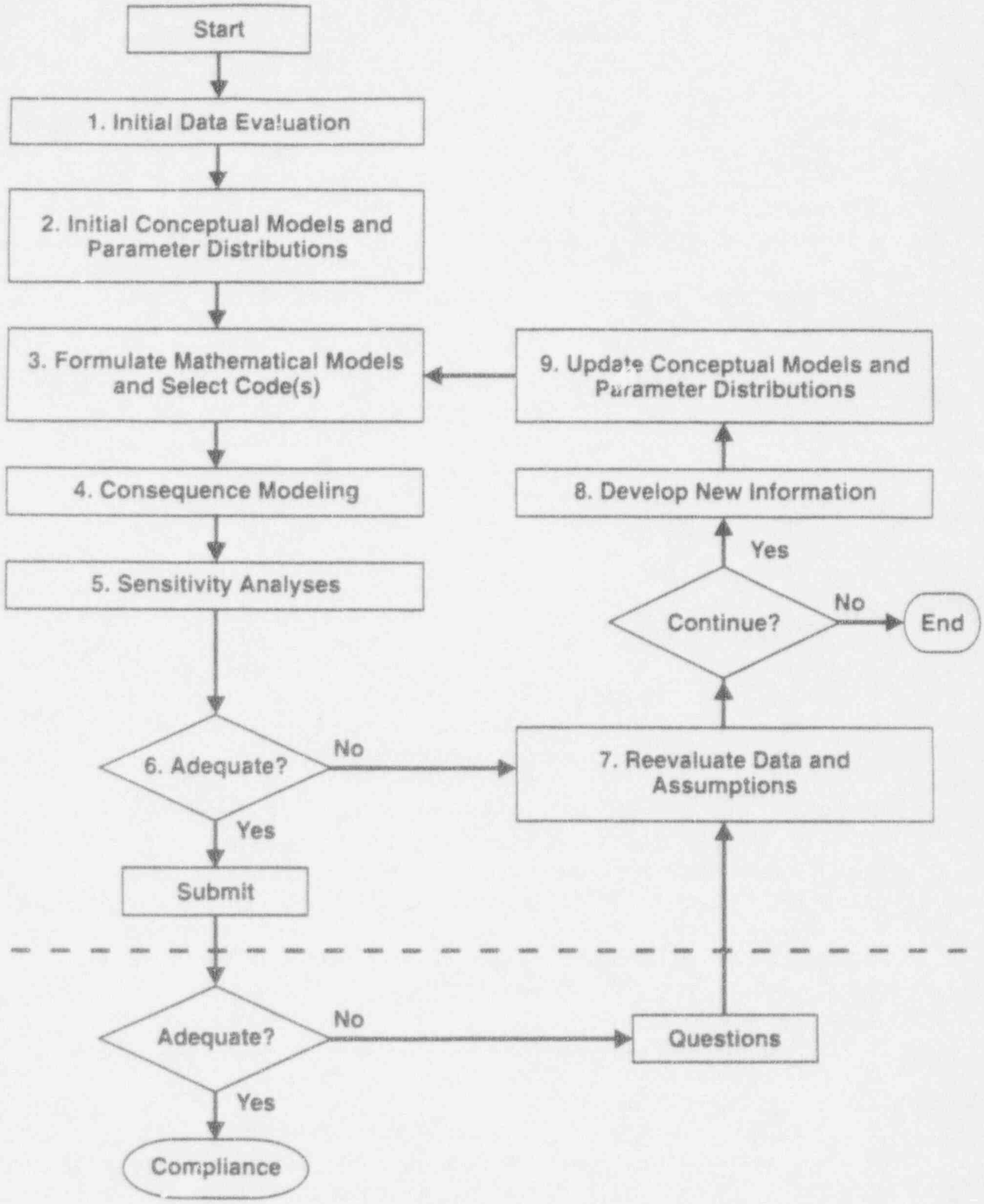


Figure 3. Flowchart of overall performance assessment process.

However, the intent is to illustrate differences between fundamentally different concepts of the behavior of the system, in contrast to different model parameterizations.

3. Formulate Mathematical Models and Select Codes: At this stage of the analysis, the analyst formulates mathematical representations of the conceptual models. These mathematical expressions will usually be represented and solved in particular computer codes. Implementation of models should be done, based on site-specific physical and chemical process considerations, and the representation of conceptual models should never be constrained by the limitations of some computer code, simply because it is available or easy to use. This may mean that the analyst may have to develop a computer code for the express purpose of evaluating a particular conceptual model. However, it is expected that this level of effort will usually not be necessary, because a large number of computer codes exist that can be used to represent a broad range of potential conceptual models. As noted in Section B.2.1, it is essential that codes and data bases used in the analysis be properly verified and documented, according to a rigorous quality assurance/quality control (QA/QC) program.

4. Consequence Modeling: The purpose of consequence modeling is to calculate doses for the different conceptual models. For each conceptual model, the analyst should propagate the associated parameter uncertainty through the mathematical models in such a way that a distribution of doses is produced. Thus, the output from an iteration of a performance assessment is a series of dose distributions, each associated with a particular model. One acceptable approach for propagating parameter uncertainty through the models is to use Monte Carlo analysis. However, the staff recognizes other approaches may also be acceptable (Zimmerman, et al., 1990).

5. Sensitivity Analysis: Sensitivity analysis is performed on the consequence analysis results, to evaluate which models and combinations of parameters were most significant in producing the resulting doses. It is especially important when the initial consequence modeling yields potential doses approaching or exceeding the performance objective. The primary functions of this step are to: (1) identify data and assumptions that affect the analysis results for careful scrutiny; (2) optimize efforts by specifying the most important information to be collected, to reduce regulatory uncertainty; and (3) identify which assumptions and parameters do not influence the results. The first and third functions are of most importance to the regulator and other parties interested in the process; the second function is of primary interest to the applicant.

   Sensitivity analyses have been effectively used to identify important parameters in high-level waste performance assessment analyses [e.g., Bonano, et al., 1989]. However, standard techniques have not yet been identified for evaluating sensitivities relative to peak dose performance measures, or for evaluating sensitivities to conceptual model (assumption) variations.

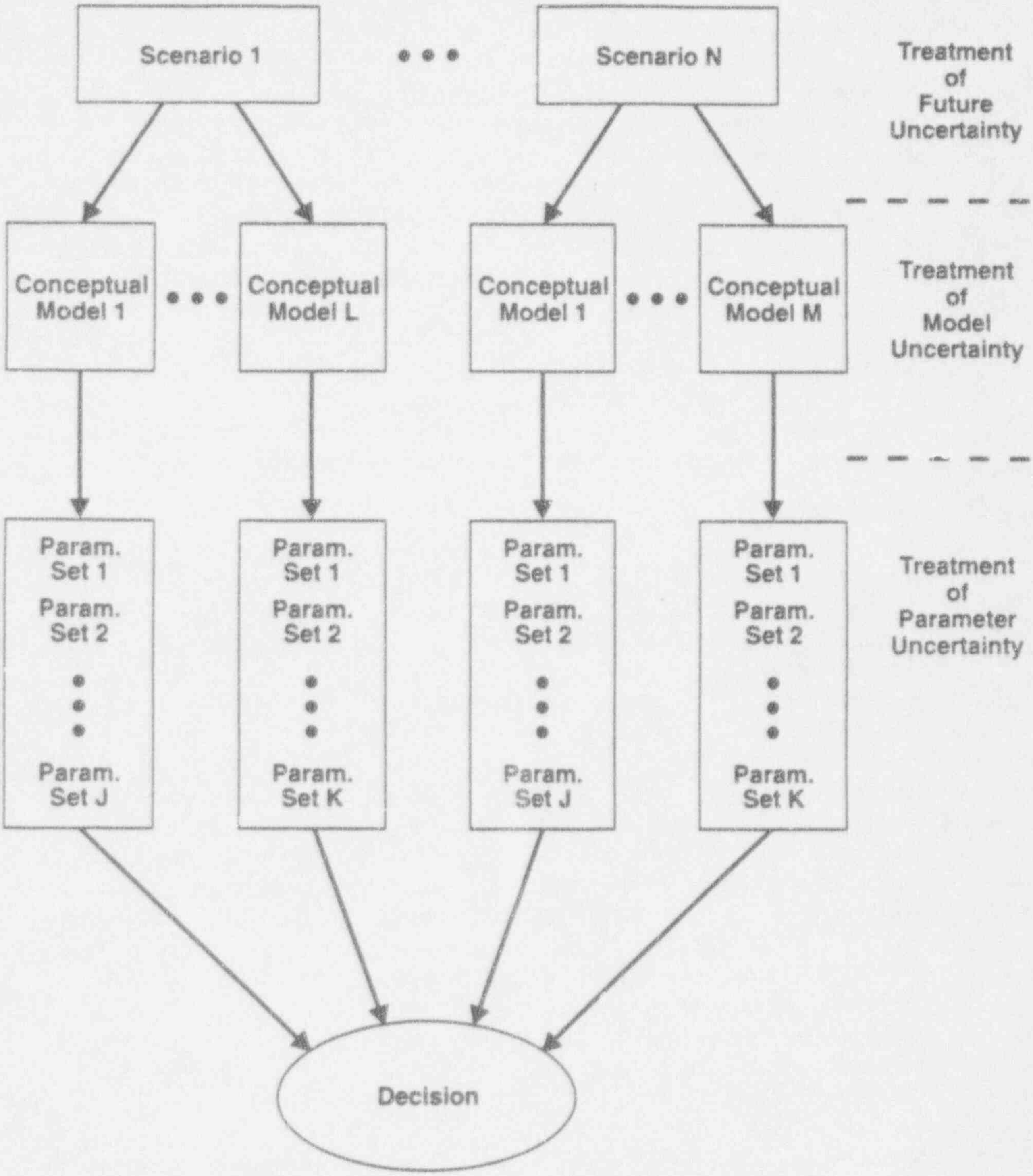


Figure 4. Overall approach to uncertainty analysis for LLW performance assessment (after Kozak, et al., 1993).

6. Evaluation of Site Adequacy: The evaluation of site adequacy is a simple comparison between the consequence analyses and the performance objectives. If the comparison shows that the performance objective has been met, the analysis is done, assuming that the analyst is satisfied that the assessment is defensible. If the comparison does not indicate that the performance objective has been met, the applicant may decide to proceed through Steps 7 through 9, described below.

   An important issue relating to the evaluation of site adequacy is to determine what part of the output distribution of doses must lie below the § 61.41 performance objective. This technical policy issue is addressed in Section D.4.

7. Reevaluate Data and Assumptions : This phase of the analysis has two functions in this performance assessment process. Both functions are performed by the applicant, as this area is primarily concerned with the allocation of resources to develop further information necessary to demonstrate compliance. The first function is to identify which information and assumptions have the greatest impact on demonstrating compliance with § 61.41. Entering into this evaluation would be the sensitivities of the result to different parameters and assumptions, the relative uncertainties of the data, the degree of conservatism, and the cost of producing more or better data. This function, which also has been called "data worth analysis" in decision making models (Kozak, et al., 1993; Bear, et al., 1992, and Freeze, et al., 1990) is related to the optimal use of resources. The second function is equally important, but again is the concern of the applicant. If the data needed to eliminate a conceptual model or parameter range from consideration are very extensive, owing to site complexity or other factors, it may be more cost-effective to reject the site and proceed with another site.

8. Gather New Information: Once sensitivity analysis has identified the critical information needed to reduce regulatory uncertainty, that information must be gathered. New information should not only be gathered to understand the disposal site, but should also be developed to help reduce regulatory uncertainty.

   Information developed can be one of four types: new site characterization data, changes to facility design, adjunct modeling studies, or new design basis information. New disposal site data may be generated by, for instance, drilling a new well. Changes to facility design might influence, for example, how barrier degradation is modeled. A new facility design might also permit adjunct geochemical modeling to be used to allow credit for reduced solubility limitations. New design basis information might consist of specifying inventory limitations, to reduce calculated off-site doses in the subsequent iteration. Any of these sources of new information may significantly affect the subsequent consequence analysis iteration. The applicant must provide adequate supporting information that justifies revising the assumptions in the new analysis.

9. Update Assumptions: The principles of this step are the same as the initial assumption step. In this case, however, assumptions are modified based on a larger

knowledge base. Subsequent model formulation may involve elimination of a conceptual model, modification of a conceptual model, or introduction of new models, as suggested by additional information. It should be noted that if the initial step included a broad range of conceptual models, the updated models will always trend toward less conservatism; however, models should always be conservative, relative to the information available when they are formulated.

A final consideration related to the defensibility of the analyses is that independent quality assurance auditors should be able to trace all modeling results, thus demonstrating that they can be reproduced. In addition the entire performance assessment process, including the iterations, should be documented. Updating data parameterization and conceptual models must be based on valid information, reasoning, and professional judgement, not simply that the analyst didn't like the result, or believed they were overly conservative.

C.3 Role of the Regulator

The burden of proof for demonstrating regulatory compliance resides with the license applicant. Once the applicant believes that an adequate performance assessment has been developed, it is submitted as part of the overall license application. It is the job of the regulator to provide an independent evaluation of the applicant's performance assessment, to determine whether it provides reasonable assurance of regulatory compliance. This is indicated in Figure 3 by the activities below the dotted line. The regulator(s) evaluate the performance assessment and develop questions about various aspects of the performance assessment. The feedback loop to the applicant is through a reevaluation of data and assumptions by the applicant. It is intended that the further iterations in the performance assessment process would be followed by license applicants who would then submit their answers to the questions. As noted above, it is important to the regulatory staff that a comprehensive documentation of the performance assessment process be provided in the application. Review of the application by the regulatory agency would not involve conducting an independent performance assessment or an independent repetition of every part of the overall process; however, the regulatory agency should follow the process as a guide to its review and to help support its regulatory findings.

Review of the license application and preparation of comments does not necessarily require execution of performance assessment codes. The regulatory staff may, however, conduct independent performance assessment modeling in selected subsystem areas, to corroborate independently the applicant's performance assessment results. The amount of independent modeling would be based on technical judgement, the level of confidence the staff has in the data, assumptions, models, and codes used by the applicant, and the relative significance of subsystem modeling results to the overall compliance demonstration provided by the applicant. As with the applicant, regulatory staff modeling should be compatible with the quality and amount of data available to support the performance assessments. At a minimum, the regulatory staff should critically evaluate the span of models and parameters used in each iteration, to ensure completeness and conservatism, and to evaluate the justification for modifying assumptions at each step of the process. That is, the license applicant should be prepared to identify which adverse conditions were considered, and how those conditions were addressed as part of the process. The regulatory review should emphasize: (1) selection of assumptions and conceptual models; (2) basis for model input data selection; (3) appropriateness of computer model application; (4) integration of subsystem models; and (5) analysis of uncertainties.

C.4 Participation of Interested Parties

Participatory performance assessment is an open process in which regulators and other interested parties work with the site developer at proposing and refuting alternative conceptual models. Two important positive outcomes to assist in building regulatory confidence may result from an open process. First, a broader range of conceptual models and potentially adverse conditions would likely be considered in performance assessment than if the license applicant were working independently, and any inherent bias on the part of the applicant to preclude consideration of possible alternative conceptual models and potentially adverse conditions would be diminished. Second, if the issues and concerns of the public and other interested parties are addressed within the process, there is enhanced potential for eliminating such issues and concerns from becoming adversarial hurdles when the application is submitted.

D. STAFF POSITIONS ON TECHNICAL POLICY ISSUES

Technical policy issues are fundamental questions pertaining to interpreting and implementing Part 61 performance objectives and technical requirements. Recommended staff positions on five key technical policy issues that affect how performance assessments are conducted and evaluated are discussed in this section. The level of guidance provided is general, since individual factors for any particular disposal site must be addressed on a disposal site-specific basis. For example, in assessing the role of engineered barriers in disposal site performance, the NRC staff recommends not relying on the behavior of the engineered barriers, for performance assessment, beyond a 500-year service life after site closure (see Section D.2, below). However, guidance is not provided in Section D.2 on how to model engineered barrier performance at various times during the service life, as the barriers degrade. Guidance on the process an applicant should follow in carrying out such a site-specific analysis, to make determinations of the degree of credit that should be afforded engineered barriers at various times, is set out in Section E, below.

D.1 Role of the Site and Consideration of Site Conditions, Processes, and Events

The natural site's contribution to overall system performance is to provide a stable environment for disposal, and to preclude or attenuate the movement of radionuclides off-site through environmental transport media (ground water, surface water, and air). The function of the disposal site should not be compromised by natural conditions and processes, or by human activities. Site performance with regard to precluding or inhibiting radionuclide transport off-site is an essential part of the performance assessment. Features of the natural site that are fundamental to assessing radionuclide transport, should be determined from a variety of investigations including: (1) geological, geotechnical, hydrological, hydrogeological, and geochemical; (2) meteorological and climatological; and (3) biological studies. The applicant should follow the iterative site characterization and performance assessment process described in Section C and portrayed in Figure 3.

The technical requirements of Part 61 specify minimum characteristics that a disposal site must have to be acceptable for use as a near-surface disposal facility. The emphasis of the site suitability requirements (§ 61.50) is on site stability, waste isolation, and long-term performance. Two of the siting requirements, §§ 61.50(a)(9) and §§ 61.50(a)(10), require avoiding sites where the frequency, rate, and extent of geologic events and processes will adversely affect the long-term performance of an LLW disposal facility or preclude defensible site modeling of long-term performance. This means that disposal sites should be selected that are both geologically stable and where natural processes are occurring at a consistent and definable rate such that the uncertainty associated with future site behavior, possibly over many thousands of years, can be captured in the performance assessment analysis.

In choosing a disposal site, §§ 61.7 (a)(2) requires that site characteristics should be considered in terms of the indefinite future and evaluated for at least a 500-year timeframe. The basis for a minimum 500-year timeframe for evaluating site characteristics is to ensure suitable site conditions for achieving long-term stability of the site and Class B and C waste forms, and the 500-year effective life of intruder barriers to isolate Class C waste disposed of at depths less than 5 meters (§ 61.7). The minimum 500-year timeframe also coincides with the period of time that the staff recommends as the maximum design life of engineered barriers (see Section D.2, "Role of Engineered Barriers"). Beyond this period of time, into "the indefinite future," reliance must be placed primarily on the site's natural characteristics to maintain the releases of radioactivity to the environment within safe levels. Specific recommendations for an acceptable general approach to the timeframe issue is provided in Section D.3, "Timeframe for Performance Assessment Analyses".

A major source of uncertainty in performance assessment is in the selection and model representation of processes and events that may occur at a site over very long periods of time and that may have a significant impact on its long-term performance. Future processes may include ongoing processes that occur over time under current conditions (e.g., change in vegetation, with time, at a site; cycles of drought and precipitation; and erosional and depositional processes). Future events may range from those that occur periodically under current conditions (e.g., earthquakes, volcanoes, and floods) to events that require significant changes in current conditions to occur (e.g., glaciation). It is in the nature of performance assessment that modeling assumptions are intended to bound a reasonable consideration of site conditions that may not necessarily correspond to future realities.

Because radionuclide release and transport mechanisms are affected by the variability of natural processes and events, a performance assessment analysis should consider a broad range of assumptions and data adequate to encompass distinct events, as well as long-term trends in natural phenomena acting on the site. For example, analyses of infiltration may need to include a range of infiltration rates that would represent both a single large wetting event as well as a prolonged period of wetting. The goal is to develop a set of processes and events that must be included in the analysis as a basis for making a regulatory decision. Thus, the models eventually adopted for the performance assessment analyses must be shown to be capable of simulating disposal site performance over a conservative range of parameters and assumptions that are used to represent natural events, processes, and conditions at the site. Specific approaches for dealing with uncertainty in a performance assessment is provided in Section D.4, "Approaches To Uncertainty and Sensitivity Analysis".

Climatic and meteorologic conditions are significant factors to be considered when designing and assessing the performance of an LLW disposal facility. It is important to note that recent concern with global climate change and studies of the geologic record have greatly increased understanding of past events and cyclical processes that control climate. Specific guidance about the development of meteorological information, as input to the performance assessment model, is provided in Section E.2, "Infiltration".

For some disposal site locations, disturbance from continental glaciation or an interglacial rise in sea level in response to a global climate change is possible. Such events are envisaged as being so disruptive regionally to the site and associated human populations as to render disposal site radiological dose assessments virtually meaningless. For disposal sites less likely to be as severely impacted by global climate change, ascertaining the nature, timing, and magnitude of related meteorological processes and events (i.e., regional consequences) and their effect on disposal site performance may be highly uncertain. Finally, the consequences of a changing climate on site performance will be mollified by the combination of radioactive decay of the short- and intermediate-lived radionuclides and site-specific regulatory controls over the amount of long-lived radionuclides disposed of at the site. Therefore, the staff recommends that site conditions that may arise directly from variations or changes in global climate do <u>not</u> need to be evaluated in performance assessment analyses.

Possible biosphere changes may be projected over relatively short timeframes of a few hundred years, but the uncertainty of future climate changes makes long-range projections on the scale of thousands of years impossible. To the extent that the natural and climatic history and geography of a site are known, there is a basis for projecting what the succession of vegetation at the site may be and for developing a reference biosphere for the performance assessment model. Nevertheless, given the uncertainty in projecting timing and extent of climatic change, an approach for biosphere changes that bounds the current trends should be considered sufficient. The analyst may assume that the reference biosphere is present throughout the period of performance that is analyzed.

Possible geosphere change may be projected over much larger timeframes than biosphere change, and the geologic record at a site can provide a great deal of information about possible future conditions, and processes, and events, including: (1) continuation of past and current trends; 2) possible changes in geologic processes; and 3) the frequency of possible disruptive events. Since the ground-water pathway is the most important one for many LLW sites, it is important to keep in mind that the uncertainty in data, parameter, and coefficient values for the ground-water system (discussed in Section E.5) does not necessarily increase with time. Significant uncertainty for the geosphere is primarily associated with our understanding of the natural site characteristics, such as its heterogeneity, and our ability to measure and extrapolate laboratory and field data, on a limited scale, to the larger scale of the site and region.

If the environmental conditions over the period of the performance assessment are shown to be similar to current site conditions, an assumption could be made that current land use practices and other human behavior continue throughout the duration of the analysis. For instance, current local practices related to well-drilling techniques may be assumed to be followed at all times in the future. If site conditions evolve to be significantly different than current conditions, as in the analysis of extremely disruptive events, assumptions about human activities should be consistent with the assumed conditions.

D.2 Role of Engineered Barriers

The term "engineered barrier," as defined in Part 61, encompasses more than what would generally be considered a "barrier" and it is therefore important to discuss the meaning of the term. As defined in § 61.2, the term means "a man-made structure or device that is intended to improve the land disposal facility's ability to meet the performance objectives in Subpart C." In general, the term encompasses human-made materials that are intended to function as barriers to infiltrating water, to radionuclide transport, or to human intrusion. It also encompasses natural materials that are reconfigured by humans in order to impart some characteristic or property that will allow the material to perform as an engineered barrier. As an example, a surface drainage system, which may consist of designed and constructed slopes and ditches that are excavated into natural materials, to provide for rapid removal of excess surface water, greater than the natural drainage, would limit the amount of precipitation that could infiltrate. This engineered feature thus improves the performance of a land disposal facility. Such a surface drainage system would therefore constitute an "engineered barrier," as defined in Part 61. A more obvious design feature in a land disposal facility that constitutes an "engineered barrier" would be a compacted clay layer in the engineered cover system. In this case, the engineered in-place properties of the clay layer would be intended to impede infiltration into the disposal unit, and thus improve the performance of a land disposal facility.

Many specific design features, for a disposal facility, that are intended to perform as engineered barriers are left to the discretion of the disposal facility developer. Although engineered barriers may be used to improve facility performance, engineered enhancements to the site cannot make up for any deficiency that would prevent the site from meeting the suitability requirements of § 61.50. Certain design features may be necessary because of specific site-related conditions, while others may function as engineered barriers, but are not relied on to enhance or improve disposal site performance, and thus no credit is assumed for that barrier in the performance assessment. It is the role of the applicant to clearly define the concept and details for any specific disposal site with engineered barriers and provide the related analyses, including the performance assessment.

The role that engineered barriers can play in performance assessment is dependent upon many factors. One of those factors includes the character of the LLW expected to be contained in the disposal unit(s). A study of the characteristics of LLW disposed from 1987 through 1989 at the three operating LLW sites in the United States (Roles, 1990) shows that although most of the activity in initial waste inventories resides in Class C waste, Class A waste contains most of the inventories of long-lived radionuclides (radionuclides with half-lives greater than 100 years). In a few hundred years after disposal, however, the higher-activity short-lived radionuclides will have decayed to the point that most of the activity remaining in LLW will be contained in Class A waste. This "cross-over" characteristic typical of currently disposed of LLW, establishes two of the most important elements that should be considered when analyzing the potential for controlling release of radioactivity off-site after site closure. These elements include: (1) the capability of the disposal site, including the engineered barriers, to isolate wastes during the time when most of the activity is present at the site, roughly the first 500 years after disposal, and (2) the ability of the natural site, and backfill, added buffers, and other chemical barriers, to continue to isolate waste and retard migration of the long-lived radionuclides off-site from an inventory remaining after most design features and engineered barriers have experienced degradation and can no longer be relied on for performance enhancement.

Therefore, the issue of the role of the engineered barriers in performance assessment becomes one of assessing the capability of the engineered barriers over approximately the first 500 years. This involves identifying and quantifying relevant material properties and characteristics as parameters in the performance assessment analysis. Engineered barriers that are integrated into a system within the land disposal facility in many instances may provide redundancy in the disposal site performance. This redundancy may influence the range of values for the parameters that should be considered in a performance assessment. Various properties of the materials of the engineered barriers may control the magnitude of the improvement that can be gained in performance; however, the performance assessment should encompass a conservative range of parameter values for a particular material. The range of values used in design must also reflect what is achievable in the field, once the various materials, configurations, and the resulting engineered barriers are integrated into the disposal facility. Once a disposal unit is ready for operation, it will be necessary to verify that the actual as-built values of the parameters used in the performance assessment are within the design range. If the as-built values of the parameters are outside the range considered as initial conditions in the design, additional supporting studies to update the performance assessment may be required.

In determining the numerical values and the confidence levels associated with the parameters that will influence the capability and service life of the engineered barrier, the span of knowledge of specific materials and their application must be considered. Some materials, such as synthetic waterstops that may be used in an LLW disposal facility, have a history of use over periods of not much more than 100 years. The long-term performance of other materials that may be used as engineered barriers (e.g., clay, sand, and gravel) is well known from their behavior in the natural environment and from proven construction experience. Based on the materials used, it will be the responsibility of the site license applicant to justify the material properties and their service life relative to performance assessment. The analyses of several issues (i.e., surface drainage and erosion protection, stability of cover slopes, and settlement and subsidence) related to meeting the long term stability requirements of § 61.44 are typically evaluated independently of performance assessment. The occurrence of certain natural events (e.g., seismic and meteorological) and resulting imposed loads that the facility must be designed to withstand, are factored into the design of the disposal facility (these "design-basis" natural events are defined in Chapter 3 of NUREG 1200). Once it has been determined that the site stability requirements are met, it can be assumed, for the purposes of performance assessment, that the engineered barriers will be stable against design basis events for their service life. In the time beyond their service life, the adverse effects that severe natural events would have on engineered barriers could be accounted for, in performance assessment, by assuming conservative material properties, to represent the degraded condition of the engineered barriers. It will not be necessary, in a performance assessment, after allowing for complete degradation of the engineered barriers, to assume the creation of complete instability that disregards the presence of the constituent materials in the degraded barrier. The degraded condition could be found acceptable if the remaining constituent materials were shown to be resistant to anticipated chemical or biological processes and no large voids would develop that could lead to instability.

In a license application review, credit for engineered barriers to improve the behavior of the land disposal facility will be evaluated by the staff on a case-by-case basis. Sufficient information and justification supporting an applicant's claim for performance of engineered barriers for any timeframe would need to be provided. In general, for periods beyond 500 years after site closure, an applicant should assume that engineered barriers are degraded, and only natural materials and site characteristics, and backfill, buffers, and other chemical barriers can be relied on, in a performance assessment, to demonstrate that the § 61.41 performance objective will be met. In the degraded condition, the engineered barriers (e.g., concrete vault, engineered subsurface drainage system, etc.) should be assumed to have the properties of their constituent materials. See Section E.3.5 for a detailed discussion on modeling of engineered barriers from their intended design condition through complete degradation.

D.3 Timeframe for Performance Assessment Analyses

A key policy issue for performance assessment of an LLW site is the time period to be used in the model calculations. A basic concept underlying Part 61 is to ensure protection of public health and safety over both short and long timeframes. The rule, however, does not stipulate an upper time limit for applying the regulatory dose standard and would seem to imply that the standard should always be applicable.

D.3.1 Objectives

An important point to consider in establishing a timeframe for analyzing an LLW site is the purpose of the modeling approach and the capabilities and limitations of the models and codes. All models are simplifications of real systems and, in general, no model can predict the exact behavior of system over either short or long timeframes. Performance assessment models and codes provide tools for evaluating a proposed disposal facility and environs for the express purpose of making a regulatory decision about its suitability (i.e., whether it is likely that the § 61.41 performance objective is met).

The objective in developing an appropriate timeframe for performance assessment analyses is to provide a period of analysis sufficiently long to reasonably demonstrate compliance with the § 61.41 performance objectives, and to determine if site-specific inventory limits need to be established as part of overall site safety.

D.3.2 Considerations

In developing a timeframe suitable for LLW performance assessment, a number of key issues need to be considered. An important point to consider in developing a timeframe is that some of the radionuclides in LLW, particularly those present in Class A waste, have long half-lives and may be present at the site over very long timeframes. Substantial inventories of long-lived radionuclides are currently being disposed at LLW sites (see Roles, 1990). Some of these long-lived radionuclides have daughter radionuclides with significantly higher dose potential than the parents.

Another important consideration is that the period of time necessary to evaluate the potential hazard to the maximally exposed individual from migration of radionuclides is a function of many parameters, most of which are determined by site-specific conditions. Thus, some transport processes may be slow enough that the calculated arrival time of a contaminant plume at a potential receptor location may range from hundreds to thousands of years after leaching begins. Even for relatively mobile radionuclides, transport to a possible receptor location in humid environments may range from a few tens of years to many thousands of years, and in arid environments substantially longer timeframes may be involved. Truncation of a performance assessment at too early a timeframe may result in the analysis failing to account for a substantial inventory of long-lived radionuclides.

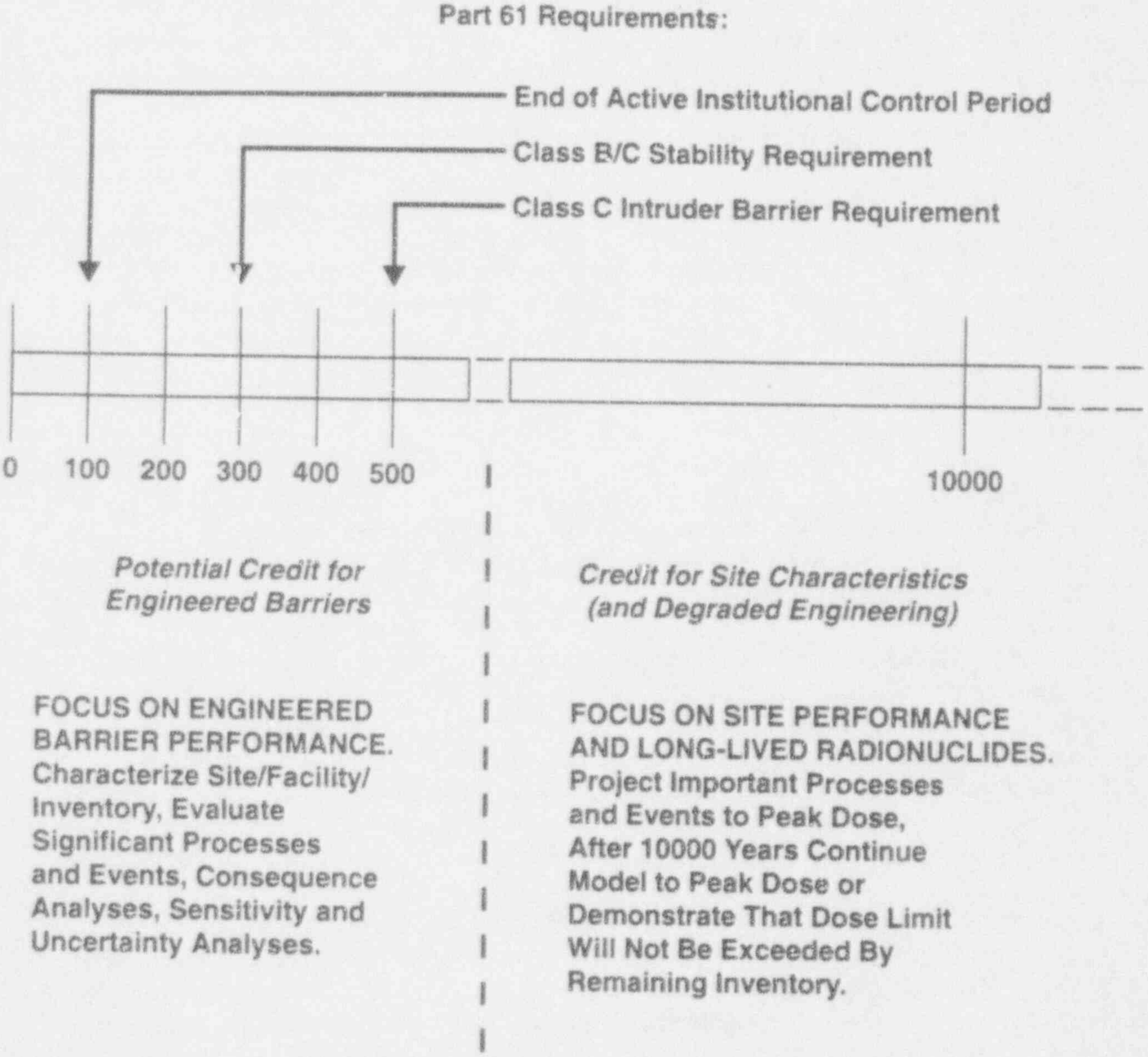
One of the fundamental concepts in protecting public health and safety, in Part 61, is to develop site-specific inventory limits on particular radionuclides that may be released from the facility to ground water. Both the DEIS and FEIS for Part 61 (NRC, 1981 and 1982) recognized the extremely site-specific nature of ground-water migration and potential impacts. Hence, generic inventory limits for ground-water protection, analogous to the waste classification system for intruder protection, are not provided in the rule. The technical analysis done in the DEIS identified four radionuclides of particular concern for migration (^{3}H, ^{14}C, ^{99}Tc, and ^{129}I), but others may also be important, depending on the particular radionuclides that are projected to be in the inventory. Both the DEIS and FEIS recommended that the total quantity of these four radionuclides acceptable for disposal at any particular site will be determined as part of the licensing process, based on the specific hydrogeologic conditions, facility designs, and operating procedures at the site. The final rule generalized the inventory limits strategy and incorporated it in §§ 61.7(b)(2), which states that "for certain radionuclides prone to migration, ... a maximum disposal site inventory based on the characteristics of the disposal site may be established to limit potential exposure." Because of the site-specific nature of the problem, development of inventory limits must be done on a case-by-case basis.

A performance assessment analysis carried out to peak dose, even if it occurs over long timeframes, provides information about the relationships between the inventory of long-lived radionuclides (and daughters), the site characteristics (under current conditions) and the potential hazard to future generations for different disposal scenarios. However, there is substantial concern that a dose calculated at some far distant time is less meaningful than at shorter time periods, because the assumptions concerning processes and events that are used in the performance assessment analysis may become invalid over long timeframes. Clearly our ability to project site and facility performa [illegible] ter major geologic events and climatic changes that may occur beyond the current ge [illegible] poch is highly uncertain, at best. Nevertheless, specifying a generic cut-off time for performance assessment analyses does not take into consideration site-specific variables that control radionuclide release, transport, and dose and their associated uncertainty. Manipulation of variables and processes (e.g., infiltration, barrier degradation, K_ds, and release rates) within relatively conservative ranges can readily move the calculated peak dose beyond a specified [illegible] d of time, without accounting for, and addressing, the possible impact that a pa [illegible] inventory of long-lived radionuclides may have on the public health and safety and the environment.

D.3.3 Approach

There are two fundamental timeframes of importance that must be considered in performance assessments of LLW disposal facilities after closure. The initial performance assessment timeframe, which is relatively short in a geologic sense, is [illegible] cerned with the integrated engineered systems performance as it degrades and the maj [illegible] of radioactivity decays to relatively innocuous levels. The second performance assessment timeframe is concerned with the long-term performance of the site, after credit for engineered systems can no longer be taken, and is primarily focused on the interaction of long-lived radionuclides in the waste and the natural features of the site. Figure 5 depicts a time-line of the approach recommended below.

The first performance assessment timeframe is related to the potential hazard for moderately high-activity short- and intermediate-lived radionuclides and the expected performance lifetimes and degradation processes for engineered features, such as multi-layered cover des [illegible], concrete vaults, high-integrity waste containers, stabilized waste forms, and intruder barriers. The main design function of these engineered features is to limit infiltration of water into the waste, so as to minimize leaching of radionuclides into the environment, and to provide protection to the inadvertent intruder. Part 61 requires stability lifetimes on the order of 300 to 500 years, for features such as B/C waste forms, high-integrity containers, and intruder barriers for Class C. As discussed in Section D.2, service lifetimes on the order of a few hundred years for engineered features are considered credible. Given the uncertainties in projecting the performance of these types of systems, it is recommended that all significant conditions, processes, and events that may affect the ability of the engineered disposal system and natural site to meet the performance objectives need to be considered for at least 1000 years post-closure. Certain features of site, such as the geosphere and design basis events like the PMF, may need to be considered for even longer timeframes. These calculations would include a parameter uncertainty analysis using ranges



FOCUS ON ENGINEERED BARRIER PERFORMANCE. Characterize Site/Facility/Inventory, Evaluate Significant Processes and Events, Consequence Analyses, Sensitivity and Uncertainty Analyses.

FOCUS ON SITE PERFORMANCE AND LONG-LIVED RADIONUCLIDES. Project Important Processes and Events to Peak Dose, After 10000 Years Continue Model to Peak Dose or Demonstrate That Dose Limit Will Not Be Exceeded By Remaining Inventory.

Figure 5. Timeframe for performance assessment of low-level waste disposal facilities.

and distributions of values for different conceptual models that represent the degradation of the engineered systems (i.e., vaults and covers), source term release rates, and site characteristics, as the disposal system evolves from its design performance to degraded performance. Within this timeframe, it is anticipated that an initial suite of peak doses will occur, due to releases of relatively mobile radionuclides (e.g., ^{14}C, ^{36}Cl, ^{99}Tc, ^{129}I) from degrading or degraded facilities, in humid environments.

Beyond 1000 years, it is anticipated that the natural site characteristics and the degraded engineered system would predominate the dose calculations in a performance assessment. The recommendation is to carry out performance assessment calculations to peak dose, assuming that the conditions, processes, and events considered significant for the site continue to occur to peak dose or 10,000 years. If additional geosphere changes are anticipated for a site between 1,000 and 10,000 years these would have to be factored into the analysis (see Section D.1 for discussion of future site conditions in performance assessment). These calculations would include a parameter uncertainty analysis, using ranges and distributions of values for different conceptual models developed for the degraded engineered systems (e.g., infiltration through degraded vaults and covers), source term release rates, and natural site characteristics (such as infiltration, etc.). If a radionuclide shows evidence of breakthrough, but has not reached its peak at 10,000 years, the calculation should be continued to its peak. The applicant should view the 10,000-year demarkation point as a general guideline rather than an absolute limit to the performance assessment analysis time. Within the longer timeframe, it is anticipated that secondary peak doses will occur, due to releases of less mobile radionuclides (e.g., U, Th, Pu, and daughters) from degraded facilities, in humid environments. However, for regions with long ground-water travel times (e.g., arid environments), this longer timeframe may correspond to the arrival of relatively mobile radionuclides.

A determination of potential impacts past the 10,000-year timeframe can be addressed in one of two different ways. One approach is to simply continue the analysis to peak dose regardless of the time at which it occurs. Staff recognizes that the assumptions and conditions of the analysis may not represent real conditions at such long timeframes. However, the express purpose of such a calculation is to determine if inventory limits may be needed. This approach would be especially useful at a site where ground-water travel times are very long even for mobile long-lived radionuclides.

An alternative approach is for the applicant to demonstrate, with reasonable assurance, that the remaining inventory on the site (in both the disposal units and in the soils and water) would not result in the dose standard being exceeded in the future. This approach would be especially useful for immobile radionuclides whose total inventory and waste concentrations are very low or whose leachate concentrations are limited by solubility to low values. For example, the applicant may be able to demonstrate that the solubility of a radionuclide, such as Th, is such that under any reasonable set of site conditions (pH, redox chemistry, ionic strength, etc.) the dose from its maximum concentration in water would always be below the performance objective.

If performance assessment analyses in any timeframe, indicate that the inventories of particular radionuclides are the source of doses that are larger than the performance objectives in § 61.41, then the applicant needs to determine if this is due to conservatism used in the analysis. If so, the applicant would iterate through the performance assessment process to become more realistic in the analysis. If, however, failure to meet the § 61.41 performance objectives is primarily a function of the inventory of a long-lived radionuclide, then the analysis would serve as a basis for developing a site specific inventory limit.

D.4 Approaches to Uncertainty and Sensitivity Analysis

Uncertainty is an inherent element of a performance assessment and needs to be considered, to provide a measure of confidence in the results. Performance assessment analyses, which use both simple and complex models of natural features and engineered systems, contain uncertainties due to limitations and assumptions of the modeling with respect to real site conditions and processes, and variations in parametric values used in the models. Such analyses typically include a large number of variables, each of which encompasses a range of probable values. Different, but reasonable, combinations of these values can lead to a range of possible results. A credible analysis will require a thorough understanding and explanation of the influence or impact of the assumptions and parametric values on the calculation of consequences. Uncertainty analyses provide a means of evaluating these consequences. In addition, different plausible conceptual models and future scenarios of site conditions (i.e., variability and evolution of the natural site conditions) may need to be considered in a performance assessment. Finally, given the large number of variables in the analysis, there needs to be a means of focussing on the most important ones. Sensitivity analyses are an essential tool to determine the most sensitive parameters (i.e., those that have the largest affect on the model result).

D.4.1 Objectives

The consideration of formal treatments of both uncertainty and sensitivity will help in determining if there is reasonable assurance that the performance objectives for Part 61 will be met. The objective of an uncertainty analysis is to determine the degree of variability in the result as a function of the cumulative variability in the input data and parameters. The objective of sensitivity analyses is to determine the relative contributions of different input variables to the resulting dose, allowing both the applicant and regulator to focus attention on the most important variables. Another important objective is to evaluate the different conceptual models of site processes and conditions. It may not be possible to reject alternative conceptual models of a site on the basis of expert judgement alone. Thus, a formal approach for evaluating alternative models needs to be incorporated into the PAM.

Existing guidance on the treatment of uncertainty in LLW performance assessment recommends that uncertainty be assessed, but does not provide detailed guidance on approaches to be used for this purpose. NUREG-1199 (Section 6.1.5.1,) recommends that the "results of the contaminant transport analyses should identify the maximum and minimum ranges and discuss the likelihood of predicted concentrations because uncertainties in the data and analyses preclude determining single concentration values." It also recommends that the applicant perform sensitivity analyses and provide the results. Similarly, for dose estimates, "the assessment of uncertainty should include analysis of uncertainties in model output, assumptions, and calculations [and] be presented as expected values accompanied by a range of maximum and minimum values" (Starmer, et al., 1988).

Because performance assessment analyses, for any particular site, may involve a spectrum of models of differing complexity, the most appropriate method(s) for evaluating uncertainty need to be tailored to the sophistication of the analysis and the nature of the uncertainties being analyzed. For example, a simple screening type of analysis (similar to what has been proposed under air transport in this document, see Section E.5.3) with a limited number of parameters may require an uncertainty analysis that focusses on demonstrating the conservative nature of assumptions inherent in the models and limited quantitative analyses with parameter values (it is possible that some sophisticated analyses would be performed to support conceptual model assumptions and parametric values). However, as more sophisticated models (typically the increase in model complexity is done to reduce conservatism by taking credit for additional processes or reduced parameter ranges) are used in the performance assessment, it becomes more difficult to analyze the effect of the modeling assumptions and parametric values on the results used to determine regulatory compliance. In contrast to what may be required for simple models, understanding the uncertainty of modeling results associated with more sophisticated models, which are likely to include a relatively large number of parameters, may require a statistical approach (e.g., Monte Carlo sampling) to assist identification of important processes and parameters associated with the analysis. There exist different degrees of complexity between these two approaches that could be used to tailor the sophistication of the uncertainty analysis to particular areas of the performance assessment that may require more attention. Thus, for example, the use of lumped parameter in place of a multi-parameter model, might be used in certain situations to reduce the complexity of the analysis, while still retaining sufficient detail so that the defensibility of the analysis is not compromised. Regardless of the approach, a credible analysis requires the justification of the modeling assumptions and selection of parameter values and an understanding and discussion of their relationship to the compliance calculation. The following section provides an overview to uncertainty and sensitivity analyses and recommends specific approaches that NRC staff will find acceptable.

D.4.2 Considerations

Several distinct sources of uncertainty in performance assessment modeling may be identified. These include: (1) uncertainty in conceptual models and mathematical models (i.e., model uncertainty); (2) uncertainty about the future state of the site (i.e., scenario uncertainty); and (3) uncertainty, in the data, parameters, and coefficients used in the models (i.e., parameter uncertainty) (see Kozak, et al., 1993; and Davis, et al., 1990).

D.4.2.1 Model Uncertainty

Model uncertainty is defined here as the uncertainty intrinsic to developing models of real sites, facilities, or processes and analyzing them. There are two general types of model uncertainty: 1) Conceptual model uncertainty, and 2) Mathematical model and code uncertainty.

Conceptual model uncertainty describes the uncertainty associated with developing simplifying assumptions for a specific site and data set. This includes uncertainty about the interpretation and use of data (e.g., parameter variability in space and time), and assumptions about system dimensionality, isotropy, initial, and boundary conditions (Kozak, et al., 1993). While models and sub-models developed for the system are designed to be "reasonably conservative" or "conservative, yet realistic", there may be credible alternative models or sub-models given: (1) limitations in available site data; (2) ambiguities in interpreting site features; or (3) inadequacies in our understanding of processes that are relevant to site performance (e.g., physical, chemical, geologic, and meteorologic processes). This type of uncertainty is intrinsic to all model development and is difficult to deal with in a rigorous numerical fashion. Uncertainty that is associated with the appropriateness of conservative assumptions about the site and facility, that are incorporated into the conceptual models, may be addressed as part of site specific-analyses, but also will involve professional scientific and engineering judgement.

Mathematical model and code uncertainty originates with approximations in the mathematical treatment of the system and the associated computer code(s) used to carry out the calculation. Uncertainties that are associated with expressing physical/chemical models of a site as mathematical equations and then implementing them as analytical and/or numerical solutions in a computer code, including possible coding errors, need to be dealt with. Verification of the codes used in performance assessment modeling should be done as part of the QA/QC process. This is particularly important when a new code is developed or a well established and documented code is modified for the performance assessment. Guidance for computer code QA/QC approaches is provided in NUREG-1200, NUREG-0856, and other NRC documents (see Wilkinson and Runkle, 1986; and NRC, 1993).

Validation of performance assessment models cannot be done in the generally accepted sense of model validation (i.e., comparing model results with the real world by calibration, history matching, and prediction), because there is no direct way of measuring actual LLW system behavior over the time-scales involved. Thus, validation efforts should be focussed on building confidence (i.e. providing reasonable assurance) that the performance assessment models are appropriate and conservative, that is, that they bound the uncertainties residing within the models and data for the site being considered. Reducing this uncertainty may require collecting more specific data and/or conducting auxiliary analyses, to address particular questions about the adequacy of a performance assessment model (as discussed in Section C.2). The development of alternative conceptual models may also be necessary to build confidence that the systems model used in the final analysis is appropriate. For certain model system components (e.g., infiltration through a proposed complex cover system), it may be possible to construct a prototype and collect data to test the system and reduce the uncertainty in the infiltration model that would be used in closure of the site.

D.4.2.2 Scenario Uncertainty

Scenario uncertainty is associated with the future processes and events that may occur at a site. Treatment of uncertainty about future states of the disposal system requires making assumptions about credible processes and events and expressing them through selection of appropriate conceptual models and input variables. It is important to recognize that the assumed future state of the system may not correspond to all possible future site conditions. Again, professional scientific and engineering judgement will be involved in addressing this issue.

D.4.2.3 Parameter Uncertainty

Parameter uncertainty is connected with the data, parameters, and coefficients used in mathematical models and computer codes. This type of uncertainty is more readily quantified than the two sources discussed above, and a large number of quantitative treatments exist, particularly in hydrogeologic modeling (see Zimmerman, et al., 1990; Maheras and Kotecki, 1990; Hoffman and Gardner, 1983). This uncertainty originates from a number of sources, including: uncertainty associated with laboratory and field measurements (e.g., standard error in analytical techniques, sampling bias errors, etc.); uncertainty in determining parameter and coefficient values used in a model (e.g., assumptions used in a pump test to determine hydraulic permeability); and uncertainty associated with the intrinsic heterogeneity of natural systems (e.g., spatial variability of measured hydraulic conductivities and distribution coefficients within a geologic unit).

There are numerous approaches for dealing with data, parameter and coefficient uncertainty (see Maheras and Kotecki, 1990; Zimmerman, et al., 1990; and Peck, et al., 1988); all require some degree of quantitative treatment. Some of the main approaches for treating uncertainty quantitatively include: (1) analytical methods, including stochastic approaches; (2) Monte Carlo methods, which include random and Latin Hypercube Sampling (LHS) approaches; and (3) Response Surface methodology, which requires development of a simple approximation to a complex model. Many of these approaches require that probability distribution functions (PDFs) be defined for the data, parameters, and coefficients.

Monte Carlo analysis consists of selecting suites (discrete sets) of input parameter values from the PDFs of the input variables. Computer runs analyzing each suite of sampled parameters in the model are called "realizations" of the parameter data set. The results of all the realizations are presented in a probabilistic distribution (histogram or PDF) of dose. Monte Carlo techniques may require large numbers of realizations, however, stratified sampling routines (e.g., LHS) reduce the number of realizations considerably (see Iman, et al., 1981). LHS sampling also allows correlations of variables to be introduced into the analysis (Iman and Conover, 1982).

D.4.3 Approaches for Evaluating Uncertainty and Sensitivity in Performance Assessment

The different types of uncertainty will require two distinct approaches in the performance assessment; one approach for scenario and conceptual model uncertainty and another approach for parameter uncertainty. Sensitivity analyses are readily accomplished within the methodology for parameter uncertainty.

D.4.3.1 Scenario and Conceptual Model Uncertainty

The recommended approach for dealing with uncertainty in the future state of the site, is to develop a "base-case scenario" of future site conditions, and processes that represent, to the extent practical, "natural" site evolution (see Figure 4). If necessary, alternative future scenarios may be developed. As discussed in D.1, not all future processes and conditions need to be analyzed in a performance assessment. For example, NRC staff does not recommend that the effects of global climate change or the effects of the next glacial cycle be factored into a performance assessment of an LLW disposal facility. Clearly one cannot predict all possible future scenarios; nevertheless, it should be possible to establish an assumed set of reasonably conservative conditions that define a "base-case scenario." If evaluation of ongoing geologic and biologic processes at a site indicate mutually exclusive scenarios of future conditions, neither of which can be rejected on the basis of additional data and/or sound scientific judgement about site events, processes, and conditions, then both scenarios should be analyzed.

An important consideration in dealing with uncertainty is the adequacy of the conceptual model to address the site and facility features, and bound significant processes and events. Treatment of this model uncertainty requires that credible alternative models must be separately analyzed if evaluation of ongoing processes at a site indicate that there are different conceptual models that cannot be resolved on the basis of additional site data. The recommended approach, for dealing with conceptual model uncertainty, is to develop a conceptual model or, if necessary, alternative conceptual models of site conditions and processes for the "base-case scenario" and also for any alternative scenarios of future site conditions (see Figure 4). In some cases, it may be possible to evaluate alternative conceptual models, within the "base-case" model, through appropriate ranges and distributions of parameters, or through suitable treatment of system component behavior through time. Results of different conceptual models should be compared and analyzed, however, averaging of different conceptual models should not be attempted.

D.4.3.2 Parameter Uncertainty Analyses

In cases where simple bounding (or screening) calculations are appropriate (i.e., in models, such as the air transport analysis discussed in Section E.5.3, where such an analysis can demonstrate compliance), the approach to uncertainty analysis is to demonstrate that the model, input parameters, and results conservatively bound the problem. In many cases, however, more realistic and complex models of overall system performance will be called for to demonstrate compliance. The use of expert judgement is essential in developing possible scenarios and conceptual models, and in identifying the types and possible ranges of parameters, however, it is not generally possible to informally and a priori identify models and parameter values that prove to be conservative throughout the performance assessment analysis. This is because of the complex relationships that exist within and between sub-models of the system and the natural variability of parameters, processes, and conditions within each system. In these cases, a formal approach to parameter uncertainty in performance assessment modeling is recommended. Within this approach, both the input variables and the output of the model(s) are in the form of PDFs (see Davis, et al., 1990).

This approach is shown conceptually in Figure 6 (modified from Hoffman and Gardner, 1983). Input parameter PDFs should be developed through both formal statistical techniques (e.g., Harr, 1987) and professional judgement, where appropriate. Parameter uncertainty should be propagated through each credible model of the system and for each particular state of the system, using Monte Carlo analyses or some similar technique. The uncertainty associated with alternative models of the system is reflected by the presentation of individual PDFs of dose for each alternative conceptual model for the "base case" and for each alternative future state (see Figure 4).

The analyst should use a distribution of input values in the analysis, because of the expected spatial variation in different properties. Use of a single value for each input in the analysis may result in potentially large uncertainties in the outcome of the analysis not being analyzed. Distributions for the parameters for the engineered system should be based upon specific values representing the median of the respective parameter distributions for each of the three phases of facility performance (i.e., design, degrading, and degraded performance, as discussed in Section E.3.5). For parameters related to the performance of the site, the selection of the functional form of the distribution should be based upon the type of distribution typically observed for that parameter. For example, hydraulic conductivities of natural materials are commonly lognormally distributed. Where no site specific data can be obtained for a parameter, the choice of type of distribution may be based upon generic information about how the parameter can be expected to vary. The parameters of the distribution should be chosen so that the distribution of the data forms a good fit with the distribution to be sampled. Some sampling programs require certain percentiles (such as the .1 percentile and 99.9 percentile) of a given type of distribution (such as lognormal and normal) to be specified. If such a program is used, care should be taken that the values specified correspond to these percentiles, rather than to other percentiles (such as the 5 percentile and 95 percentile).

In general, the analyst should carefully consider whether it is possible to reduce the number of free variables in a model. This might be done, for example, through appropriate correlations, or by developing a lumped parameter. Thus, if changes in particular parameters (e.g., Kd's for some radionuclides) occur due to variations in another parameter (e.g., soil pH or clay content) and a functional relationship can be developed, then the independent parameter that is causing the variation could be sampled and the dependent parameters computed from the functional relationship. This technique will reduce the number of parameters to be sampled, give a better picture of the effect of the variability of each parameter, and reduce the problem of correlated parameters being treated as randomly distributed. In some cases, it may be appropriate to develop a lumped parameter (e.g., a flux range of water percolating into a vault through a multi-layer cover) that represents the output of a model involving a multitude of variables. Parameters which can be specified as single values, because the uncertainty is small relative to the value itself, are suitably described by constants. In other cases, it may be appropriate to set a parameter equal to a constant value that conservatively bounds the range of values that could be possible for that parameter. However, the applicant must demonstrate that the constant value chosen is conservative relative to what would occur for the site and facility and also relative to possible combinations with other parameters in the model.

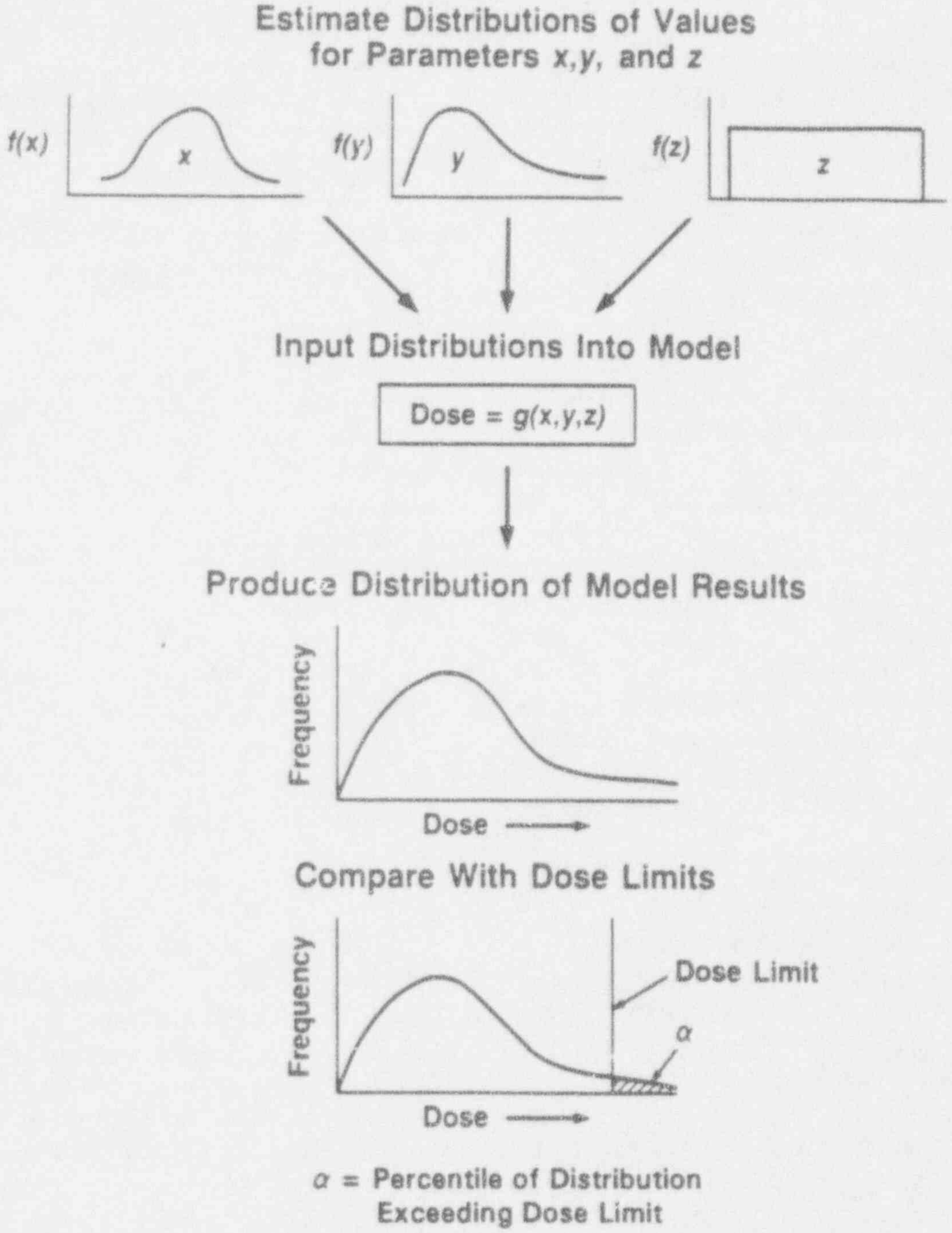


Figure 6. Conceptual approach to parameter uncertainty analysis (modified from Hoffman and Gardner, 1983).

D.4.3.3 Parameter Sensitivity Analysis

Sensitivity analyses can readily be accomplished within the framework of a formal uncertainty analysis. Often a sensitivity analysis will use the simulation results from the uncertainty analysis as input to statistical software to determine parameter sensitivity. A performance assessment is typically comprised of a number of assumptions and parameters, all with varying degrees of importance to calculate consequences. Sensitivity analysis offers a means of focusing areas of inquiry, by both developers and regulators, to those parameters and conceptual models of the greatest consequence to the result. The sensitivity analysis could be used to justify the subsequent use of simpler models and/or to reduce the number of parameters to be included in further uncertainty analysis. The results provide insights for the analyst and help in understanding of site and engineering performance.

When many parameters are uncertain, it is recommended that sensitivity analyses be based on sampling schemes that evaluate the numerous interactions (e.g., Monte Carlo sampling procedures that vary all parameters simultaneously). These types of analyses can provide information on both sensitivity and uncertainty. Sensitivity analysis procedures that examine variations of the result with respect to a single variable, while holding all other variables constant, can help identify individual parameters that the result is most sensitive to. However, this type of procedure, by itself, does not provide information on the overall uncertainty associated with the variations of a single parameter in conjunction with variations in other parameters. Where sensitivity studies are desired on a single or a limited number of parameters, while holding all others constant, the constant values should be those that gave the mean of the dose distribution created for the uncertainty analysis, and possibly those resulting in realizations near the dose standard of § 61.41.

D.4.4 Treatment of Uncertainty in Regulatory Decision Making

D.4.4.1 Conceptual Model and Scenario Uncertainty

The significance of each credible model, and each credible future state of the system, to the outcome of the performance assessment cannot be determined analytically. The analyst must weigh the results of all analyses and cogently present the evidence and arguments supporting or rejecting each model and future state of the system. Since the regulator must evaluate the overall performance of the system, in part on the basis of the applicant's performance assessment (as well as on the basis of independent analyses), it is essential that the applicant present a reasonable, comprehensive, and persuasive interpretation of the results, in the context of the applicant's understanding of the site and disposal system. For the regulatory decision-maker, it is important not to place undue significance on the results of any single model or future state of the system. Because probabilities of scenarios are not assigned to scenarios, the approach for uncertainty analyses being presented here does not formally address the probability of a particular scenario occurring. The applicant should analyze and the regulator should consider alternative conceptual models if they cannot be rejected either on the basis of additional site information, or on the basis of scientific knowledge and judgement of processes occurring at the site. In general, where there are two or more equally reasonable and plausible conceptual models for the site, the conceptual model giving higher doses will be considered as a basis for making a regulatory decision about the site.

D.4.4.2 Parameter Uncertainty

The distribution of doses from the conceptual model that is determined to be the basis for making a regulatory decision (i.e., the one used to demonstrate compliance), may produce some realizations of the data that exceed the performance objectives in § 61.41 (see Figure 6). A number of factors must be considered by the regulator in determining if these cases fall within the scope and meaning of reasonable assurance.

An important consideration is to determine if a sufficient number of realizations of the parameter data set(s) have been done such that a stable output is obtained. For random sampling, in a Monte Carlo analysis, there is no predetermined minimum number of realizations. The analyst needs to determine the stability of the output distributions for the number of realizations that are intended to be used in demonstrating compliance with § 61.41. In general, the central tendency of the model will be more stable than the tail of the distribution. A significant change for the tails of the dose PDFs in two subsequent suites of realizations of the same input data set would indicate that a stable result has not been achieved and that a larger number of realizations is necessary. The stable dose distribution may follow a known probability distribution function, such as lognormal, gamma, etc. The applicant may determine if this is the case using an appropriate statistical technique (see Bowen and Bennet, 1988). For example, a goodness of fit test, such as the χ^2 test, or other similar tests, could be applied to determine the significance level of the correlation between the sample distribution and the parent distribution. However, the dose PDF may not fit a well defined distribution and such a demonstration is not essential for regulatory purposes. The analyst should examine two different regions of the stable dose distribution used for compliance.

One region of interest is the neighborhood around the mean, median, and mode that represents the central tendency of the model or the "best model estimate" of performance. The analyst should present a reasonable and comprehensive interpretation of the results in the context of their understanding of the site and disposal system. In particular, the analyst should understand and be able to explain the overall performance of the system with respect to variations of the input parameters and how the uncertainties and sensitivities of different parameters affect the result. In all cases, there should be a high degree of confidence that the mean, median, or mode of the dose distribution (whichever is highest) is less than the performance objective in § 61.41. For acceptable methods of computing a confidence level that a specific portion of a distribution is below a given quantity, see Bowen and Bennett, 1988 (pp 183-188) and Conover, 1980 (pp 95-117) 1988)]. Note that this is a necessary, but not a sufficient condition for demonstrating compliance.

The other neighborhood of interest is the upper tail of the dose distribution, especially the neighborhood of the distribution that may approach or exceed the dose standard. The analyst should understand and be able to explain how different combinations of parameters determine this region. This is of particular interest to both the regulator and the applicant, because reasonable uncertainties in parameter combinations may cause the standard to be exceeded.

In evaluating this region, both the applicant and the regulator need to consider the conservative nature of the input data sets and PDFs. Although the tails of a particular parameter distribution may represent extreme, but plausible, conditions at the site for that parameter, the simultaneous occurrence of extreme values for different parameters may not be plausible. Hence, the results need to be examined to determine if particular combinations of parameters that result in the standard being exceeded are due to unique and extraordinarily unlikely combinations of site conditions or if they correspond to reasonable parameter combinations that simply have a lower probability of occurring together. A related, but different problem is the possible combination of parameter values that could not physically occur. Professional judgement will play a role in determining the plausibility of different parameter combinations. In addition, the problem may be reduced through the use of appropriate correlations for the affected parameter values.

The approach, to performance assessment modeling discussed throughout this technical position, is designed to ensure that the model results provide a conservative upper bound to actual disposal system and site performance. Thus, if the consequence analysis shows a certain percentile of the upper tail of the dose distribution exceeds the dose standard (e.g., see Figure 6), it does not necessarily indicate a similar probability of system failure. Because of the site and facility specific nature of the performance assessment model, and varying degrees of conservatism that may be incorporated into different models and data sets, NRC staff is not specifying generically what percentile, if any, of the dose distribution in the compliance model may exceed the standard and still provide reasonable assurance that the performance objectives will be met by the disposal system (both the natural site and engineered features). Such a determination must be made on a case-by-case basis.

D.5 Role of Performance Assessment During Operational and Closure Periods

Section 61.53 requires that during the operational and closure periods, the facility operator is responsible for conducting an environmental monitoring program. Measurements and observations must be made and recorded to provide data to evaluate potential health and environmental impacts and long-term effects of the facility. In addition, § 61.80, requires licensees to maintain records, by waste class, of activities and quantities of radionuclides disposed of, and report to the Commission the results of environmental monitoring and any instances in which observed site characteristics were significantly different than those described in the license application.

The incorporation of new information (e.g., site monitoring data and actual inventories) should be used to reassess assumptions and estimates of parameter ranges in the performance assessment models. A framework for determining the value and impact of this new information on the calculation of concentrations and doses should be developed and documented (Massman, et al., 1991). If there is sufficient information to question the performance assessment input, then additional performance assessment analyses focusing on the potential uncertainties should be performed. For instance, if the waste spectrum changes significantly, the performance assessment should be updated to ensure that the regulatory requirement is still met. Additional performance confirmation should also be considered, for engineered aspects of the disposal facility, in cases where assumptions made during the initial performance assessment are amenable to confirmation during facility operations. For instance, the as-built permeability of concrete or the performance of the engineered covers may be tested to ensure that the performance assessment assumptions remain conservative relative to the as-built facility. New site characterization data will not necessarily be required during the operational period, given that geological and hydrological aspects of the performance assessment should have been treated with sufficient conservatism when the initial license application was granted. However, if there is a perceived need to collect data for other purposes (such as expanding the monitoring well network) these data may be used to update the performance assessment.

E. PERFORMANCE ASSESSMENT MODELING ISSUES AND RECOMMENDED ANALYTICAL APPROACHES

E.1 Introduction

The principle that uncertainties inherent in analyzing LLW site performance can be adequately addressed with models and analytical approaches that are based on reasonably simplified conservative representations of real LLW disposal systems is the cornerstone of the guidance presented in this technical position. Therefore, an important decision in developing a performance assessment of an LLW facility is the selection of an appropriate model and analysis method for each performance assessment system component. After the analyst has identified significant sources of uncertainty, analysis methods ranging from very conservative simple analytical solutions to much less conservative complex numerical techniques may be chosen depending on the degree of uncertainty about processes or conditions being analyzed and their significance to overall site performance. As shown in Section C "Low-Level Waste Performance Assessment Process", this approach to performance assessment becomes a powerful tool for making regulatory evaluations about site safety when it is integrated into and used to direct the activities of site characterization.

The PAM was introduced in Section B "Background" of this technical position. Given the diversity of disposal facilities that are likely to be developed within the various States and compacts, and the current state of knowledge about modeling facility performance over time, the goal of the PAM is to provide a basic set of analytical approaches for conducting performance assessments. Although the overall performance assessment strategy, sub-models, and related uncertainties have not changed, the analytical approaches recommended in this section of the technical position have evolved, based on staff and NRC contractor insights obtained from applying the PAM to a site-specific test case problem. This illustrates the versatility of the PAM concept when it is applied, within an overall performance assessment process, to build an ensemble of models and codes suitable for addressing site-specific assessment needs.

Comparisons with the annual doses allowed any member of the general population after site closure should be based on calculations of radiological exposures from releases of radioactivity at human access locations that would produce the highest likely dose to a single individual. This individual is termed the maximally exposed individual. The maximally exposed individual is a hypothetical person, and as the term implies, no actual member of the general population would be anticipated ever to receive doses equaling or exceeding the maximally exposed individual. The maximally exposed individual is assumed to reside at the site boundary, where off-site exposures to radionuclides released to air and water are expected to be greatest, and consumes locally grown food crops irrigated with contaminated ground-water withdrawn at the site boundary. In the technical approaches described in this section of the technical position, radiological concentrations in individual environmental transport media (air, ground water, surface water) and pathways are input to an integrated dose assessment to determine the maximum total dose to a single individual off-site.

Locations for human access to radionuclide transport media are considered to be the following. For ground water, an off-site well is assumed to be drilled at the boundary of the disposal site, unless this location is physically unreasonable. This off-site well should be assumed to be located at the point along the site boundary that produces the maximum radionuclide concentration in ground water. Air pathway doses should be calculated at the point along the site boundary that produces the largest doses from inhalation. Surface-water pathway doses should be calculated at the closest actual point of ground-water discharge at the surface, unless some other point produces larger doses or is physically more reasonable. For instance, if calculating doses due to eating fish at the nearest point of discharge is physically unreasonable, doses would be calculated farther down stream, at a point where fish could realistically be taken.

The components of contaminant flux impacting the maximally exposed individual must ultimately be converted to an annual effective dose equivalent so the effect of the scenario may be assessed relative to the performance objectives. Taken together, the modular conceptualization and implementation of the performance assessment methodology (see Figure 1), and the iterative performance assessment process recommended in Section C.2 of this document (see Figure 3), favor a formal integration of the individual process sub-models. Although it is possible to step through the performance assessment process manually, creating input to one sub-model based on the results of another sub-model, the NRC staff prefers a formalized integrating element; an overall "systems" code that controls the sub-models or codes and automates the inter-model linkages represented in Figure 1 by pathway segments.

Although automating the inter-model linkages adds considerably to the amount of problem-dependent computer code that may need to be written, the benefits derived from the automation and formal integration are significant. These benefits include:

(1) The ability to easily step through another iteration of the performance-assessment process makes it much easier to assess the sensitivity and robustness of the system and gain valuable insight into the system;

(2) The opportunity to provide a higher degree of quality assurance than that achieved with a purely manual system (typographical errors can be virtually eliminated);

(3) The automation of the linkages forces an explicit recognition of and consistent

approach to assumptions that might be vague or addressed inconsistently, if the linkages remain manual; and

(4) The assurance of consistency of parameters and values is generally more likely for a system that is controlled by an overall systems code.

E.2 Infiltration

E.2.1 Introduction

The primary objective of the performance assessment infiltration analysis is to determine the amount of water entering the disposal unit, and the amount of water available for replenishing the ground-water system (i.e., natural recharge). Determining the amount of water infiltrating into the disposal unit is needed in the source term analysis to determine the release rate of radionuclides from the disposal unit. Knowledge of recharge in the natural system is needed in determining the upper boundary condition for the ground-water flow and transport analysis.

The term infiltration is commonly defined as the entry of water into the soil surface. For purposes of this document, the term infiltration analysis is being broadened to also include the subsequent movement through the soil or cover system and ultimate entry into the disposal unit or ground-water system.

Figure 7 shows the various processes to consider in assessing the infiltration of water into a typical disposal unit and in determining the amount of water available for ground-water recharge. Climatic, soil physical properties, and vegetation are all important in controlling the amount of infiltration. Each of these features can vary both spatially and temporally; therefore, trying to account for them, over a prolonged time period, will involve a considerable amount of uncertainty. Several important considerations to weigh in undertaking the infiltration analysis are discussed below. A general approach to the infiltration analysis is provided after the discussion on some of the important considerations. This approach is designed to address the considerations identified below without treating them in full detail.

E.2.2 Key Considerations in the Analysis

E.2.2.1 Temporal Variation in Processes and Parameters

Highly transient processes (e.g., precipitation, runoff, drainage, evapotranspiration, and snowmelt) influence infiltration. This creates special problems in analyzing infiltration in an LLW performance assessment. The highly transient nature of these processes may require an analysis at small time increments to capture the true interaction of the various processes; however, this is somewhat problematic for performance assessment analyses that may cover many hundreds of years. As an example, water budget analyses are commonly based on average annual values. Such analyses may greatly over-estimate infiltration in humid areas, because they don't capture the true subsurface response to short-duration, high-intensity

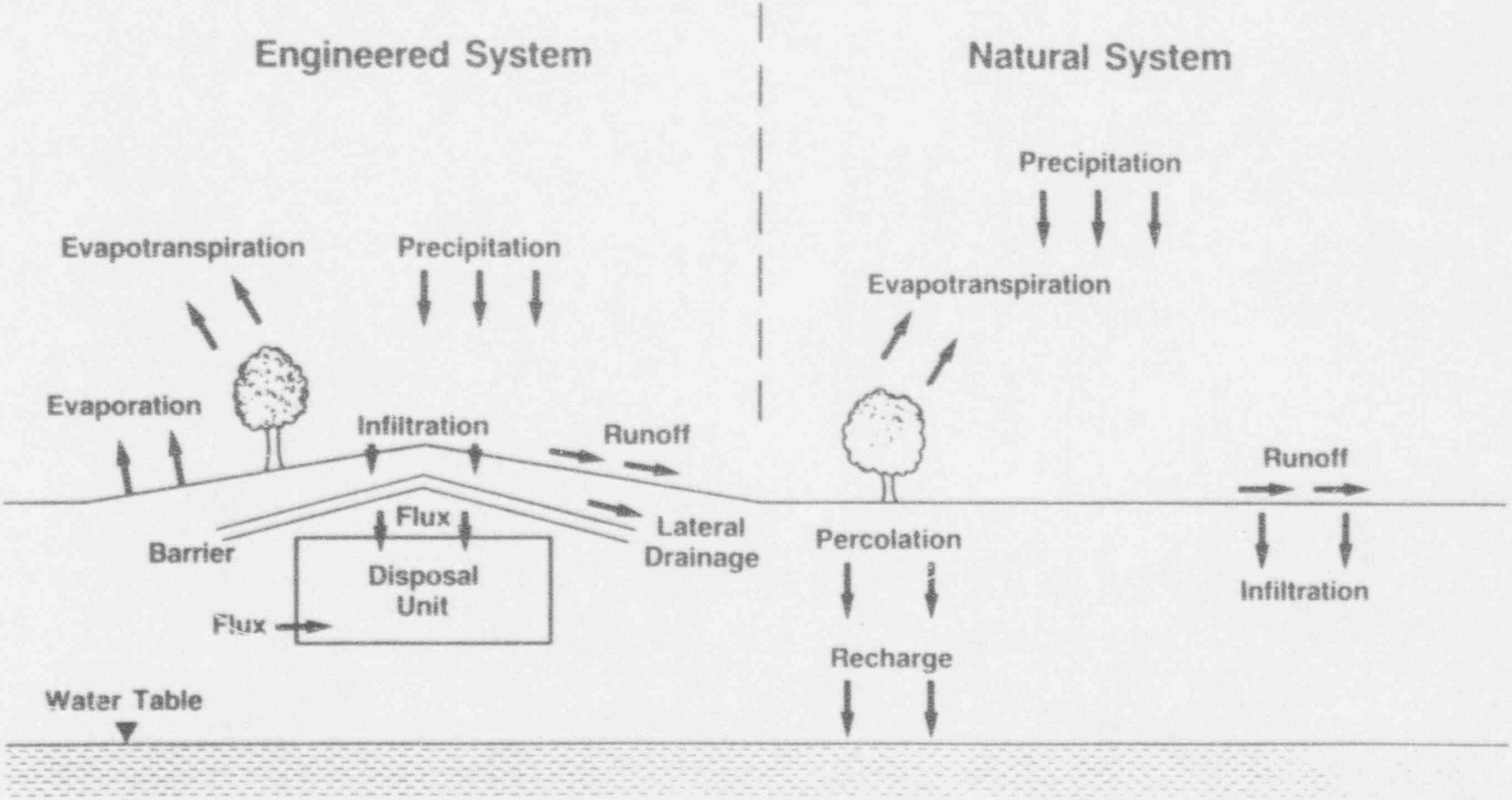


Figure 7. Schematic of processes in infiltration analysis.

rainfall events that occur during a given year. Although such an approach may be conservative, it points to some of the potential uncertainties in the analysis. Further, concluding that recharge at arid sites will be negligible because, on average, evapotranspiration exceeds precipitation is not conservative because it is entirely possible for some recharge to occur after episodes of high intensity precipitation or snowmelt. Smyth, et al. (1990) reported that 1-hour or 6-hour incremental data may be required to define the subsurface response to climate, vegetation, and near-surface soils. It can be easily seen that even for an analysis using data on 6-hour increments,the data requirements will be substantial for an analysis carried out for many hundreds of years. Even if the analysis is carried out at small time increments, consideration must be given to selecting the appropriate climatological or sequence of climatological data, to use in the analysis.

Since site conditions affect infiltration, some assumptions also must be made about the future state of the site (Kozak, et al., 1990b). Making the assumption that site conditions will remain the same throughout the time period covered by the analysis may not be conservative. As an example, a change in vegetation or loss of vegetation may enhance infiltration (Gee, et al., 1992; Smyth, et al., 1990).

There is also the consideration that physical properties of cover materials will likely change over time (see Section D.2). The cover may be affected by plant and animal intrusion, settling and slumping, and erosion. In addition, man-made materials such as concrete are expected to degrade over time, in response to physical, chemical, and/or mechanical processes (Walton, et al., 1990). As a result of these likely changes, infiltration into the unit may increase over time; therefore, an analysis based solely on as-built conditions may not be conservative. In addition, the analyst will have to consider how the materials are likely to degrade. Assumptions on how the cover is expected to change may affect the type of analysis required. For example, assuming that the concrete will degrade through fracturing will require consideration of fracture flow.

E.2.2.2 Spatial Variation in Parameters

Soil properties are expected to vary spatially over the area covered by the infiltration analysis. Variability in physical properties within soils are important in determining infiltration rates. Gee, et al. (1992) show how spatial variation in soil texture influences recharge. Variation in soil physical properties, unless accounted for, increases the level of uncertainty in the performance assessment infiltration analysis.

Even for relatively uniform soils, for example, within units of an engineered cover, physical properties can vary a great deal from one place to another. As an example, hydraulic conductivity values measured in radon barriers of three Uranium Mill Tailings Radiation Control Act (UMTRCA) projects varied spatially between 1 to 2 orders of magnitude. Variations in natural soils will be likely even higher. Consideration also needs to be given to dimensionality of the analysis. Assuming strictly vertical, one-dimensional flow should be conservative for most situations, because it does not account for lateral drainage; however, under some conditions this assumption may not be conservative. Covers designed for LLW disposal facilities will likely incorporate one or both of the following design features: a sloped surface to enhance runoff and a sloped subsurface interface of coarse-to-fine grained soil to enhance lateral drainage. This design, under some circumstances, could actually enhance water flux into the disposal unit. For example, Smyth, et al. (1990) reported that surface runoff has been observed at the cover edge of several UMTRCA projects. If this accumulated water migrates back toward the disposal unit, which it could, under some circumstances, the flux of water into the disposal unit will be larger than that assumed under strictly vertical, one-dimensional flow.

E.2.3 Recommended Approach

E.2.3.1 General Strategy

The analysis will begin with a conceptualization of the engineered system and the unsaturated zone of the natural setting. The level of detail within the conceptual model should be commensurate with the need for demonstrating compliance with the performance objectives. For example, in developing a conceptual model of the cover, the analyst may choose not to take credit (in terms of limiting infiltration) for liners of synthetic materials that may have a short life-span; such liners may provide an extra measure of protection, but may not be needed for demonstrating compliance. However, their exclusion may help to simplify the analysis.

The approach recommended by the NRC staff for the infiltration analysis is to start simple and progress to more complicated analyses, as required for demonstrating compliance and as required by the design. A simple analysis will facilitate testing several conceptual models over a range of parameter values. Figure 8 diagrams one approach. It is very similar to the integrated numerical model approach described by Smyth, et al. (1990). This approach is designed so that sites with favorable hydrologic conditions can take advantage of these favorable conditions, while sites with less favorable hydrologic conditions will require greater reliance on the engineered system.

As discussed in Section C.2, a broad range in values should be used to characterize the parameters used in the analysis. A range in values is used in order to capture the uncertainty in the parameter. A single extreme value is not recommended, as this may not be conservative when placed in the context of the overall performance assessment analysis; that is, while a particular value may be conservative for the infiltration analysis, it may not be conservative for the overall performance assessment results. As pointed out in Section C.2, the analyst should propagate the parameter uncertainty through the performance assessment analysis.

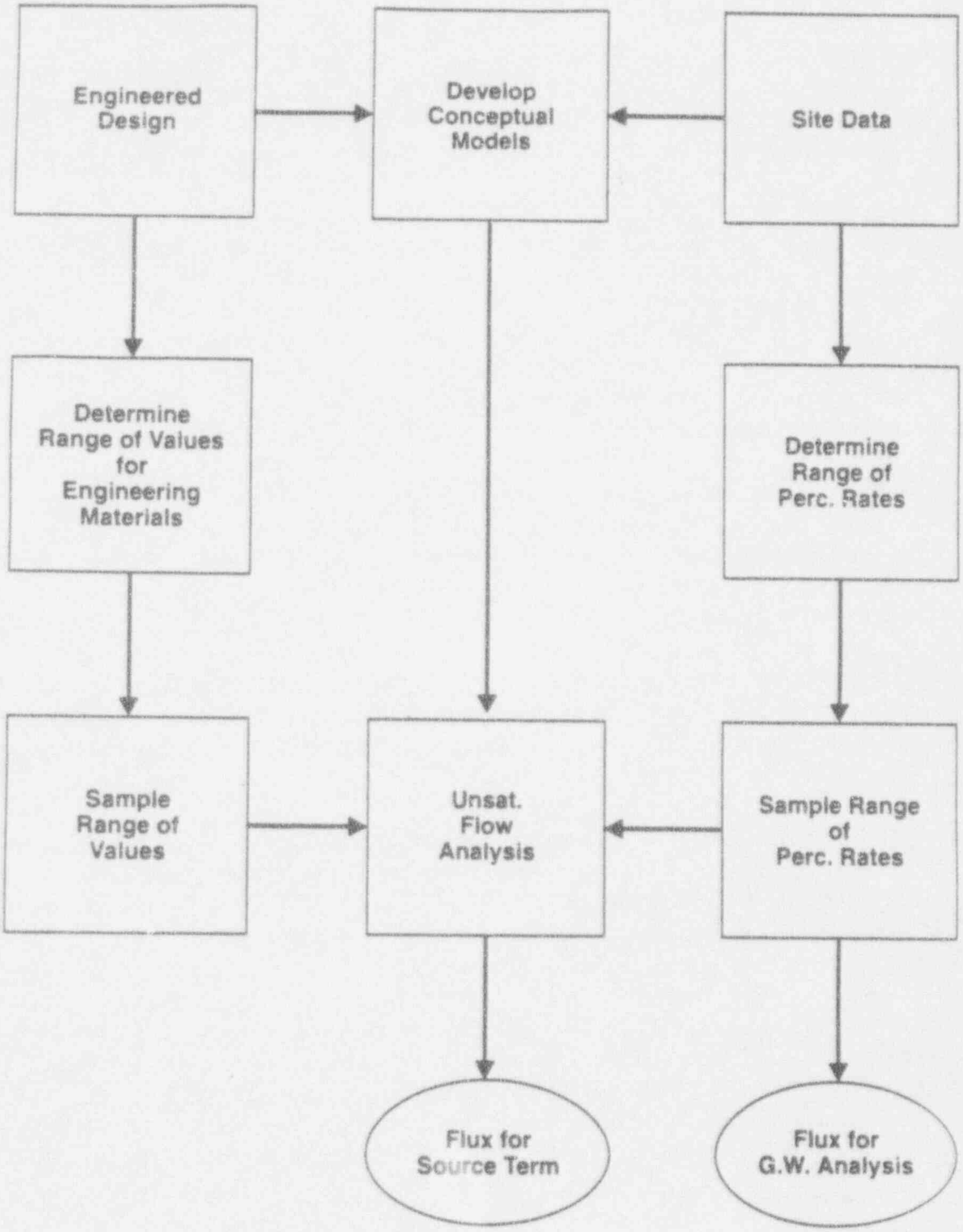


Figure 8. Approach to the infiltration analysis.

E.2.3.2 Analysis

The infiltration analysis can be viewed as consisting of two primary components. The first component of the analysis is to determine the flux of water, within the upper soil surface, that is under the influence of plant transpiration. The second component is to determine the flux of water into the disposal unit resulting from the moisture movement through the cover system.

As water moves below the zone of influence of plant roots, the transient nature of the surface processes become less important; as a result, the flux of water below this zone can be assumed to be at a steady rate. Therefore, in the proposed approach, this "steady rate" of water flux or percolation is used in determining the upper boundary condition of the unsaturated flow analysis. The percolation rate for the natural system (which is equivalent to the natural recharge) should be used in establishing the upper boundary condition for the ground-water flow and transport analysis.

When the cover is assumed to be intact, the amount of water transmitted through the cover may be sufficiently small that the analysis can be further simplified with some conservative assumptions. For example, the analyst may simplify the analysis by assuming full saturation for the clay barrier and using the saturated hydraulic conductivity of the barrier as an estimate for the percolation rate.

Because of the uncertainty in determining a percolation rate, the analyst should use a range of values in the analysis. This range should be based on the assumed statistical distribution of percolation rates. Once the range and distribution is established, values can be statistically sampled for use in the flow analysis.

In determining the range of percolation rates for the analysis, the analyst should consider the effects that discrete high-intensity events or various prolonged wet periods might have on percolation. In general, prolonged periods (i.e., seasonal or annual) of higher than normal precipitation have been found to result in more infiltration than short-duration, extremely high- intensity storms. The analyst should also consider the effects that slowly melting snow accumulated on the site may have on infiltration. The analyst should try different scenarios to determine their effects on the percolation rate. Because of the uncertainty in predicting climatic changes, the NRC staff does not recommend considering long-term climatic changes in the analysis (see Section D.1); however, variations in weather conditions should be considered, as discussed above. The analyst should also consider the effects of having no vegetation on the cover surface of the disposal unit in the event that the vegetation later dies off.

One suitable method for determining the range and distribution of percolation rates is the method used by Smyth, et al. (1990) in their analytical stochastic analysis of an UMTRCA cover. In their analysis, percolation rates were assumed to be uniformly distributed. The range in values was derived by estimating the minimum and maximum possible recharge rates. In general, such an approach should be conservative (for the infiltration analysis) since recharge rates are expected to have either a gamma or log-normal distribution, based on previous works that have shown climatic data to be best represented by a gamma distribution (Richardson and Wright, 1984), and both hydraulic conductivities and infiltration rates to be approximately log-normally distributed (Cook, et al., 1989).

Another suitable method, especially for arid areas, is to use field tests conducted at the site. Gee and Hillel (1988) discuss a number of methods for determining natural recharge and some of the considerations of each method. Of these methods, lysimeters and tracer test appear to be most reliable for estimating natural recharge at an arid site. These methods could provide an estimate of the expected recharge or percolation rate; however, the analyst will have to establish a justifiable range about this expected value, taking into account spatial and temporal variation. Kozak, et al. (1990b) recommends using several methods, as opposed to a single method. Each method used should have data input independent of the other methods.

For humid sites (i.e., greater than 500 mm (20 inches)/year of precipitation) water balance analyses may be appropriate; however, this will require some consideration of transient surface processes. For such analyses, the analyst should use National Weather Service and/or U.S. Geological Survey climatological data, from nearby stations, to augment site data. Data record for the analysis should cover 20 to 50 years (Smyth, et al., 1990). As previously mentioned, the analyst should consider variations in the sequence of weather data, to determine the effects on the percolation rate; this will likely require some type of parametric analysis. In general, water balance calculations for arid or semi-arid areas will have large uncertainties.

The second component of the analysis is to determine the flux resulting from the subsequent movement of percolating water through the remainder of the cover system. The steady rate of water determined from the percolation/natural recharge analysis can be used in establishing the upper boundary condition for the unsaturated flow analysis. For the native soils, recharge can be used directly, in establishing the upper boundary condition for the ground-water flow and transport analysis.

Because of the expected spatial variation in hydrologic properties, the analyst should use a range of values. Distributions for the parameters for the engineered system should be based on specific values representing the median of the respective parameter distributions for each of the three phases of facility performance (i.e., design, degrading, and degraded performance, as discussed in Section E.3.5). The selection of the functional form of the distribution should be based on the type of distribution typically observed for that parameter (see Section D.4.3.2 for further discussion). Values can be sampled from the assumed distribution and treated as an effective parameter in the analysis. Because the potential number of parameters to be sampled could become fairly large (depending upon the complexity of the cover system), the analyst should carefully consider the correlation of the various parameters. If parameters are correlated, it may be possible to use a lumped parameter in the analysis and reduce the number of parameters to be sampled. Parameters which can be specified can be described by constants.

Since the cover is expected to degrade with time (see Section D.2), hydrologic parameters used in the analysis will also have to encompass expected changes over time. In the approach outlined in Figure 8, degradation of materials is handled through changes in their hydraulic properties. In this way, the materials are assumed to change in a step-wise fashion. The NRC staff recommends treating the materials as a continuous porous media; therefore, explicit modeling of fracture flow is not required for materials that are susceptible to fracturing. In considering degradation of engineered materials, the analyst will need to consider the degradation not only of the clay barrier, but also of other units, within the cover, that are important to limiting infiltration. For example, over time, drainage layers may become clogged and therefore lose their effectiveness in transmitting water away from the disposal unit. An upper bounds to the flux into the disposal unit, under degraded conditions, may be assumed to be the upper bounds of the site's natural recharge rate.

The analyst should consider the influence of multidimensional flow; this is needed to ensure that accumulated water at the cover edge does not reach the disposal unit. Accumulated water at the edge may produce a larger flux into the disposal unit than that occurring vertically at the top of the disposal unit. Determining the potential occurrence of such a phenomenon will likely require a multidimensional analysis. However, once it has been determined that such accumulated water could migrate into the disposal unit, the effects can be accommodated within a simple one- or quasi-two-dimensional analysis used as part of the performance assessment analysis.

E.3 Engineered Barriers

E.3.1 Objective of Engineered Barrier Analysis

The objective of the engineered barrier analysis in performance assessment is to establish model representations of the physical characteristics and dimensions of the designed engineered features, and to determine the ranges of parameter values that would reasonably represent the behavior of the features, with the passage of time. The following discussion addresses the major issues relevant to evaluating the performance of engineered barriers, and describes a process that can be used to establish parameter values of materials in engineered barriers for use in performance assessment. The methodology for modeling engineered barriers in performance assessment is depicted in Figure 9.

E.3.2 Features and Dimensions of Engineered Barrier Systems

Engineered barriers are components and systems designed to improve the waste retention capability of a land disposal facility. The considerations related to physically describing the features of the engineered barriers in performance assessment are the same as those inherent in their actual design. These design considerations are described in detail in Chapter 3 of NUREG-1200, and are controlled primarily by the requirements of established building codes and engineering practice. The results of the design (layout and physical dimensions of a vault system, etc.) provide the information that is needed to model the physical dimensions of engineered barriers. Not all design features will necessarily be reflected in, or qualify for, consideration in performance assessment as engineered barriers. The applicant should

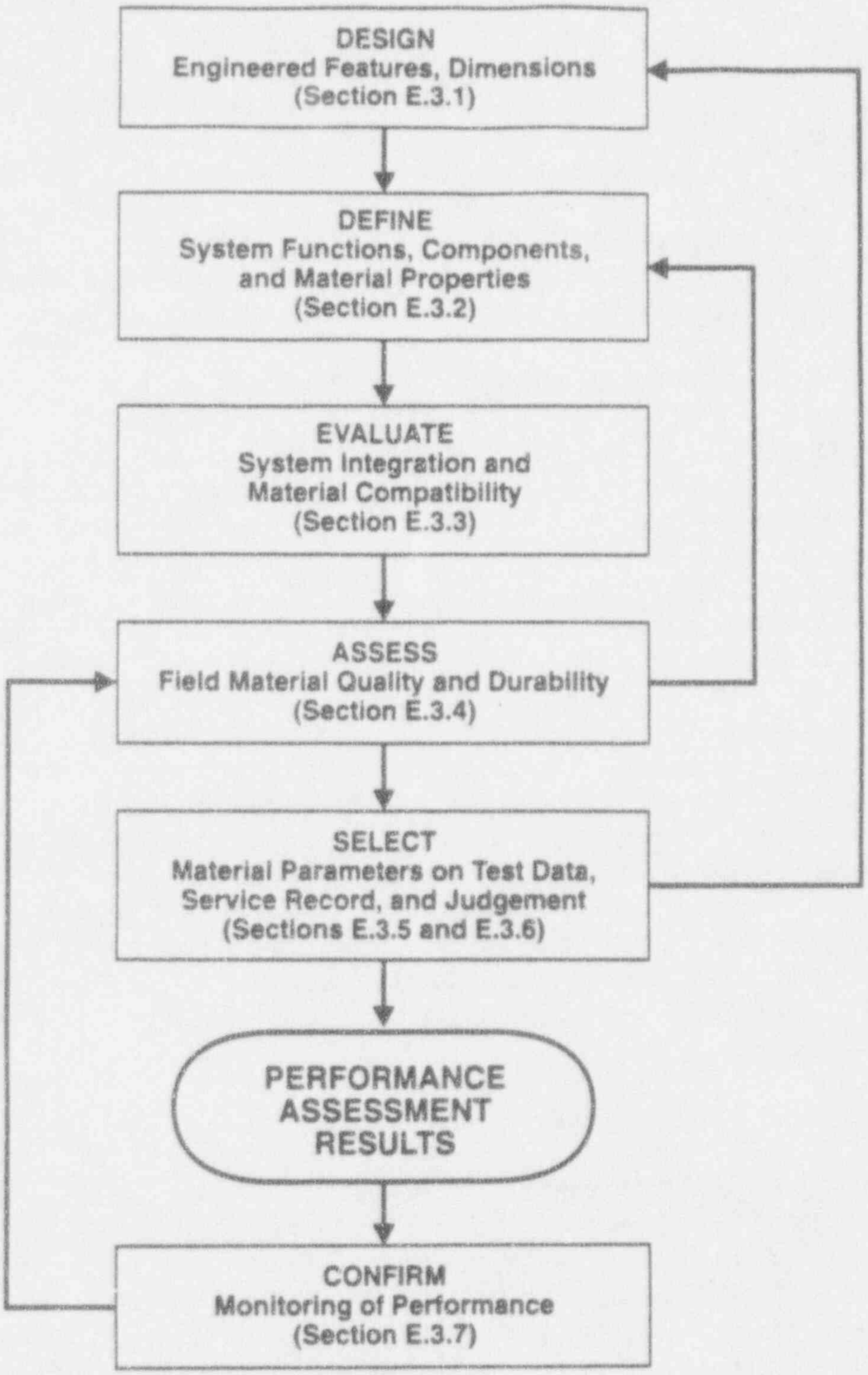


Figure 9. Methodology for modeling engineered barriers in performance assessment.

define which components and associated materials are intended to help meet the performance objective and thus are being considered as engineered barriers in the performance assessment. The design concept of a disposal unit for a land disposal facility is typically documented and depicted in sketches and drawings. The descriptions should identify the materials and their arrangement, in a disposal unit, including variations in vertical and horizontal directions. This information serves to define the physical relationship among the various types of materials that are used in a facility. It is likely that the results of preliminary performance assessment studies will be used to assess the need for additional performance enhancements that may, in turn, dictate the use of improved or additional engineered barrier systems. In this manner, design features and engineered barriers would evolve from important conclusions arising from performance assessment results.

E.3.3. Integration and Interaction of Materials

An understanding of the nature of materials in engineered barriers, their make-up, and their interactions is needed in performance assessment, for estimating material longevity and for developing parametric values that represent the behavior of engineered barriers with time. Once the various materials that make up the engineered barriers and their spatial relationships are described, it will be necessary to evaluate how their integration into the composite system affects facility behavior. Presumably, each material that constitutes part of the design is selected either for fulfilling the regulatory requirements or for some utilitarian purpose such as constructibility. Factors that need to be considered in this process include: (1) compatibility among materials that may come in contact with each other, either directly or indirectly through material transport processes within the engineered barrier system; (2) the manner in which the disposal facility is to be constructed, including how construction joints, changes in geometry, penetrations, etc., may affect system behavior; (3) the effect that failure of a design feature or some portion of an engineered barrier would have on the overall behavior of the barrier; and (4) how the degradation of material properties affects barrier performance over time. The purpose of this integration step is to start the analyst through a logical thought process, to ensure that all relevant materials and conditions that could affect the behavior of the waste disposal system over the design life of the engineered barriers are considered.

E.3.4 Construction Quality and Testing

The quality level to be required and maintained during the design and construction of a disposal facility should be reflected in the parametric values for engineered barriers derived for use in performance assessment. Before construction of the disposal facility, the quality level of the various material and construction specifications that will be documented in the license application can be used by the performance assessment analyst. It would be necessary, however, to conclude that the quality level being proposed is attainable and that it is supported by an acceptable QA program. Provisions also should be made in performance assessment for the fact that the actual level of quality achieved in the field may be different and possibly lower than that assumed during the design and analysis phase of the project. If this has not been considered in the original design, by allowing for design margins, appropriate parameter distributions in a performance assessment will need to be modified to reflect as-built conditions. For example, it is expected that the permeability of the various engineered barriers will be a key parameter in performance assessment. Therefore, it may be necessary for appropriate controls to be initiated in the field during and after construction, including testing, to verify design and performance assessment analytical values of permeability. Testing of in-place reinforced concrete barriers, for example, including areas with discontinuities, should include tests for hydraulic conductivity. Field permeability testing should also be performed on other materials and engineered barriers that are relied on in performance assessment.

E.3.5 Model Input

After proceeding through the initial four steps depicted in Figure 9, the performance assessment analyst should have sufficient information on which to base reasonable bounding values for the engineered barrier parameters relevant to performance assessment. The specific steps include: (1) identifying engineered barriers, systems, and materials used in the disposal unit; (2) appraising compatibility and interactions among materials; (3) evaluating material quality and durability, and system behavior; and (4) assessing the effect of construction quality. The analyst should also review the sources of information on engineered barrier material properties and performance, to be certain that the sources include: (1) comparable historical laboratory and field service data, including consideration of: (a) compatibility with current LLW disposal conditions and (b) compatibility of the test methods and procedures; and (2) the analytical methods for service life performance projections, including: (a) capability to address synergistic effects, and (b) the ability to extrapolate service life and performance characteristics.

Barrier performance may be divided into at least three phases, to establish ranges of parametric values for representing the performance of materials in engineered barriers with the passage of time. The first phase is the service life or performance period, when engineered barriers would perform as designed. The second phase, following the service life period, represents a time of decreasing engineered barrier function, because of ongoing processes of degradation. The third or final phase represents performance where complete degradation has occurred. Complete degradation does not imply the creation of void spaces, but rather complete loss of intended design function, and in most instances, a return to the constituent materials. For example, complete degradation of concrete would assume a return to the constituent sand and gravel aggregates, whereas, for a degraded clay cover soil, the clay soil particles would remain but at a loss in intended engineering properties. The selection of parameters for model input is very much influenced by the availability of information and data on material quality and durability. Because the timeframe to be evaluated in performance assessment is much longer than actual material performance records, conservative judgments need to be made with respect to performance. Parametric values, selected in performance assessment, to represent materials in engineered barriers during each of the performance phases, may be derived following the steps preceding the selection step shown in Figure 9.

It is expected that, in the first phase, the design performance period of different barriers will vary significantly because of the inherent diversity and variability of materials used to construct engineered barriers. This would need to be accounted for in performance assessment. As an example, following the steps in Figure 9, the hydraulic conductivity for the low-permeability portion of the cover, such as a clay layer, may range from 1E-7 to 1E-8 cm/sec over its service life. Its service lifetime may be established at 500 years because, for example, it is determined that site conditions allow roots to penetrate the clay at 500 years. Also, following the process depicted in Figure 9, the hydraulic conductivity over the service life of a reinforced concrete vault may be estimated to range from 1E-9 to 1E-11 cm/sec. If, for example, it is determined that site conditions could lead to slowly developing differential settlement under structural loading and ensuing concrete cracking 100 years after site closure, then the service life of the vault would be chosen at 100 years.

For the second and third phases of performance following the service life phase, new sets of parameter values would be established for barrier materials, first to represent engineered barriers in the process of degrading and then to represent them after they have completely degraded. Thus, to represent variations in the behavior of clay beyond 500 years after roots have penetrated, and of a cracked vault concrete beyond 100 years, additional hydraulic conductivity distributions for the respective barriers would have to be determined. In preliminary modeling of engineered barriers, the time element can be considered as a step function by introducing, at the beginning of each phase of barrier performance, the set of unique parameter distributions representing the performance of the barrier over the respective phase. In later iterations of performance assessment, continuous time functions may be established, based on as much actual data as available. Although various other approaches may be used, the acceptability of the representation of the engineered barriers in a performance assessment should be evaluated on a case-by-case review, by the regulatory agency.

E.3.6 Role of Engineering Judgment

It is important that some established and recognizable system be used to allow for and control engineering judgment in establishing reasonably conservative numerical values for relevant parameters. The staff position given in Section D.2, which recommends limiting credit for engineered barrier performance to generally 500 years, is itself a judgment made by the staff. This judgment is influenced by the increasing uncertainties in the future behavior of engineered barriers that raises questions about the reasonableness of allowing for continued design performance of most engineered barriers much beyond 500 years. Because of the uncertainties involved in assessing the performance of many of the engineered features over a long expanse of time, it is recommended that the method used by the analyst at arriving at the various numerical values for material properties be clearly documented. The documentation should include a description of the scope of expert judgments and the qualifications of those making the judgments. The distributions of parametric values established by engineering judgment will not necessarily be unique or be unanimously derived by qualified individuals. Such judgement will more likely result in a range of distributions. The important issue is that the parametric values used to represent the behavior of the engineered barriers with respect to time, should be no less conservative than can be technically and logically supported, even if limited to a consensus of engineering judgment. It is important that the process used to arrive at a conclusion be clearly defined so that someone not directly involved can trace the decision-making procedure and understand the basis for determining the established parameters. It is the responsibility of the applicant to convince the regulatory body that the judgments are reasonable and conservative and result in meeting the regulations.

E.3.7 Post-Construction Monitoring and Evaluation

During the design and construction stage of facility development it is necessary to plan for and implement physical arrangements and instrumentation needed for monitoring the relevant parameters previously defined by the designer (White, et al., 1990, and Marts, et al., 1990). If, after having developed and commenced a post-construction monitoring program, monitoring indicates that all the monitored parameters are within the original design envelope, no further performance assessment analyses are needed. However, if the post-construction monitoring program indicates that monitored parameters are outside the design envelope, a revised performance assessment would be called for. Such an evaluation and its results may also dictate the need for remedial action.

E.4 Source Term

The objective of a source term analysis is to calculate radionuclide releases from disposal units as a function of time. Within the context of a performance assessment, the source term modeling uses input from the infiltration analysis (i.e., the calculated flux of water through the barrier into the disposal unit) and provides output to the environmental transport models. The source term modeling, for the purposes of this document, needs to consider the various features of the disposal units that affect radionuclide releases. Therefore, considerations of the LLW inventory, waste types, waste form, waste containers, backfill, and chemical conditions may be needed, to estimate releases. The variation in these components, and the complications arising from the numerous interactions between them can impose significant data requirements and technical support for analyses that attempt to take credit for enhanced performance due to specific attributes or behavior of any of these components. Generally more conservative approaches will require less sophisticated analyses and support than approaches that put more reliance on predicting and understanding the behavior of complex processes. The purpose of this section is to provide guidance on the types of simple calculations that can be made and reasonably defended with current models and to give some insights on the considerations that will need to be addressed if more sophisticated analyses and/or performance credit is taken for either the waste container, waste form, or characteristics of the inventory. A schematic depicting the general considerations or decisions that could be required in a source term analysis is shown in Figure 10. The remainder of this section will discuss in detail these general considerations.

E.4.1 Inventory of Radionuclides in LLW

E.4.1.1 Issues

Radionuclide inventories that are used in performance assessments to demonstrate compliance with the dose requirements of Part 61 must be addressed on a facility- and site-specific basis.

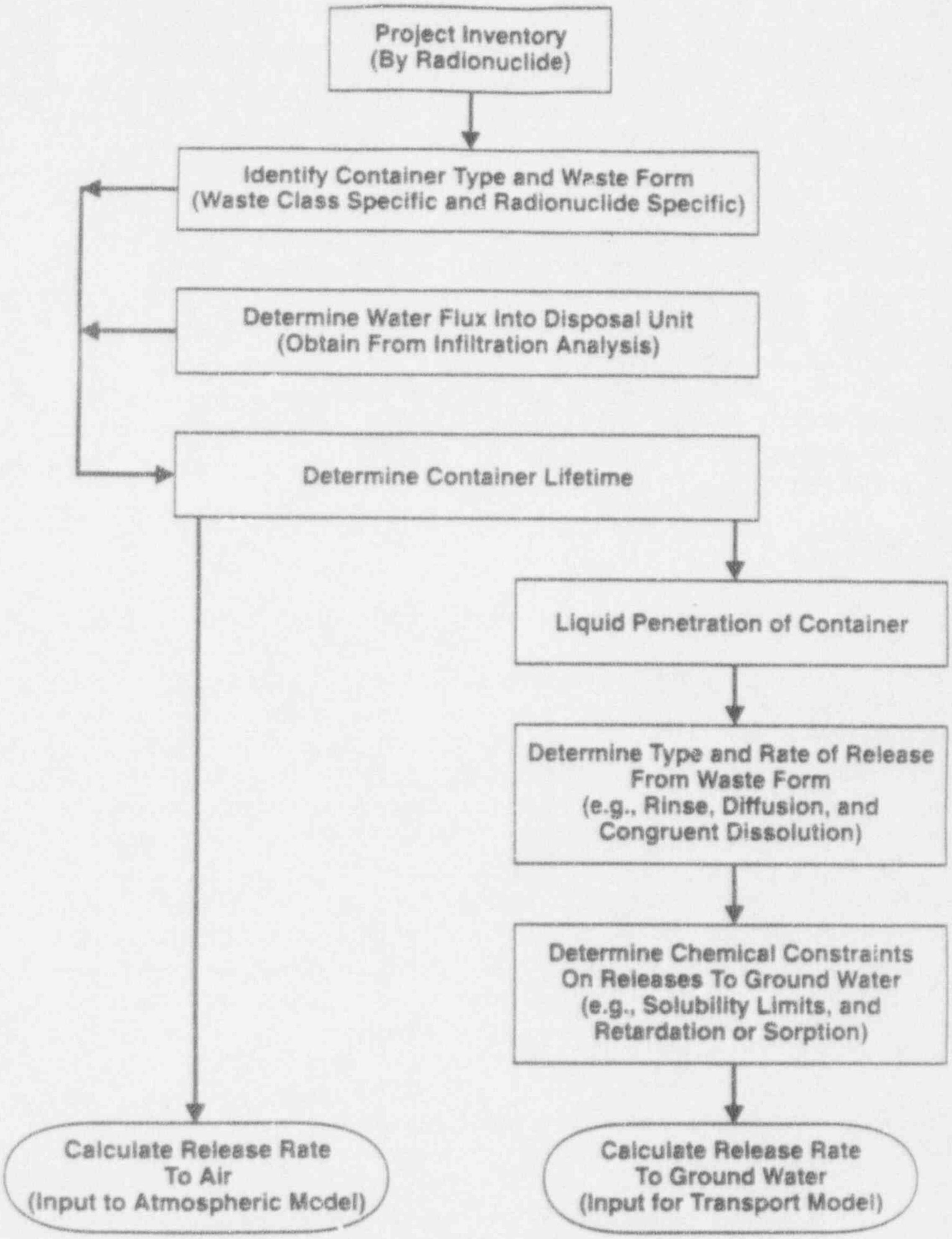


Figure 10. Calculational considerations in estimating source term releases.

Note that the calculational steps and parameters can be specific to a waste class, waste stream or an individual radionuclide.

That is, the distribution of specific radionuclides in the LLW disposal facility inventory must be known by waste class (Classes A, B, and C), waste type, waste form and waste stream. This information may be important to provide an understanding of the nature and expected behavior of certain significant radionuclides, in assessing their release from the disposal units and subsequent transport in the environment. The level of detail required to calculate the source term and to determine an acceptable inventory of LLW radionuclides depends on many factors. These include both physicochemical properties of the waste disposed of and the degradation properties of the containers. One area of concern is the distribution of radionuclides among different waste types (e.g., dewatered ion-exchange resins, activated metals, dry solids, dry active wastes, etc.); this may be important to estimating the source term over time, where each radionuclide might be expected to have a different release rate, depending on waste type. In addition, there are important timeframe concerns, if significant quantities of long-lived radionuclides are projected to be in the inventory, because they may be present at the site long after any credit can be taken for the engineered features of the disposal units. Another concern is the formation of radioactive daughter products from the decay of radioactive parents, because the daughter's dose conversion factors must be taken into account, over time, to obtain true dose estimates.

E.4.1.2 Approach

The licensee should provide a complete description of all LLW to be disposed of at the facility. All significant radionuclides present in LLW should be provided by volume and activity levels and identified by waste class, waste type (e.g., ion-exchange resins, dry active wastes, and dry solids), waste form (e.g., cement-solidified, activated metals), waste stream, and waste container for each industry (e.g., utility, medical, industrial, government, college) expected to have a different release rate, depending on waste type. LLW containing chelating agents (e.g., decontamination waste) needs to be identified separately, because of the concerns § 61.2 and § 61.20 attribute to LLW containing chelating agents. Particular attention must be given to the identification of long-lived radionuclides that may be present in LLW (e.g., C-14, Tc-99, I-129, and alpha emitting transuranics), including those not specifically listed in Table 1 of § 61.55 (e.g., Th, U). Significant ingrowth of daughter radionuclides should be included in any assessment. Trace amounts of long-lived radionuclides (e.g., Cl-36, Mo-93) that could be present in some waste (e.g., activated materials) should be identified and may need to be included in the performance assessment if not initially screened out.

General information on commercially generated radionuclide distribution by waste generators, waste class, waste stream, and waste form is available from shipping manifests (see Roles, 1990 and Cowgill and Sullivan, 1993) and the U.S. Department of Energy's (DOE's) National Information Management System (MIMS) managed by the Idaho National Engineering Laboratory. Specific inventory information for a performance assessment should be obtained from surveys of waste generators within the compact or State and from projections of changes in waste streams over the lifetime of the facility (e.g., for anticipated reactor decommissioning).

E.4.2 Screening Methods to Identify Significant Radionuclides

E.4.2.1 Issues

The objective of preliminary screening of the LLW facility inventory is to determine the key radionuclides to be analyzed in the performance assessment and eliminate insignificant radionuclides from further analysis. The use of a screening approach to determine these key radionuclides could involve a number of possible approaches and also will likely involve disciplines other than the source term (e.g., ground-water transport and dose). A tiered approach could be used that starts with the most conservative and progresses to a more detailed approach, if further reduction in the number of radionuclides is considered necessary. The simpler more conservative approaches would tend to be "back-of-the-envelope" type of calculations, but would also tend to retain more radionuclides for further analysis. Regardless of the approach, documentation would be required to explain the rationale and justification for eliminating radionuclides from the analysis.

E.4.2.2 Approach

The following are acceptable screening approaches to determine which radionuclides in the facility inventory need to be considered further in the LLW performance assessment.

1. Elimination of radionuclides with half-lives less than 5 years, that are not present in significant activity levels and do not have longer-lived daughter products.

2. In the second approach, no credit is given for the waste container, waste forms, backfill, or other retardation methods to retain radionuclides within the disposal units (i.e., a rinse model is used). All radionuclides are assumed to be available for radionuclide transport in soil to the ground-water system, and with subsequent transport to the nearest maximally exposed individual, by all exposure pathways, including drinking water. Important radionuclides will be determined by calculating the transport of the radionuclides in soil and ground water, with an acceptable radionuclide transport model, using conservative, site-specific radionuclide distribution coefficients to retard radionuclide movement in the soils. Those radionuclides whose dose potential is less than 1 percent of the Part 61 dose requirements can be eliminated from further performance assessment calculations. Appropriate computer models, such as PAGAN (Chu, et al., 1991), would be useful to make these type of screening calculations.

3. For those radionuclides exceeding the 1 percent criterion described in Item 2 above, additional evaluations could be performed; however, enough calculational enhancements will tend to eliminate differences in the screening analysis and the total performance assessment analysis. One possible additional refinement to the analysis, described in Item 2 above, would be to take credit for the retention capability of the backfill, to delay the release of radionuclides from a disposal unit.

E.4.3 Waste Container

E.4.3.1 Issues

For the source term, credit could be taken for containers in delaying any release of radionuclides, allowing short-lived nuclides to undergo significant decay. Containers for LLW typically consist of carbon-steel drums, low-specific activity (LSA) steel boxes, liners, or HICs. Data on the distribution of LLW by waste containers is generally not available. In some cases, it may be possible to estimate or infer LLW distribution by container. For example, Class A wastes are generally disposed of in LSA boxes or 55-gallon drums; Classes B and C wastes are generally disposed of in liners or HICs. A liner has no specific definition and could imply anything from a steel drum to a polyethylene-lined, thick-walled steel parallelepiped. With the exception of the HIC, the primary purpose of the waste container is to provide stability during handling (at the origin and the disposal site) and transportation of the waste.

A HIC is designed to provide the structural stability required by §§ 61.56(b) for waste forms that cannot provide it by themselves. HICs can be constructed of Ferralium 255, stainless steels, polymer-impregnated concrete, high-density polyethylene (HDPE), or combinations of these. There is considerable uncertainty and argument as to the length of time that these containers will provide isolation from the environment, especially for HDPE HICs with a concrete overpack. Initial performance assessment analyses will need to investigate the impact of the length of time for which the HIC will provide integrity against water penetration on facility performance. The selection of this "leak- proof" performance lifetime of the HICs would tend to have high uncertainty. Assumptions would need to be defensible, and the effects of site and vault chemical characteristics and design would have to be considered. The lifetime of the HIC could have a profound effect on the facility performance, whereas the lifetime of other containers (if any is assumed) could have very little effect on performance, since they will have decayed long before engineered barriers are compromised.

E.4.3.2 Approach

The locations and relative positions of individual containers within each waste class in the disposal facility need not be considered in any performance assessment, unless a licensee believes this level of detail is important.

For metal containers, the lifetime could be estimated by corrosion models. The chemistry of corrosion in soil processes is generally based on a generic data base, the use of which could lead to large uncertainties in the predicted corrosion rates (see Sullivan and Suen, 1989). The effects of internal corrosion by the waste streams would also have to be considered.

For source term modeling, the failure mechanism of HICs would probably be general (or complete) failure. In this model, the container is completely functional up to the time of failure, and after that time is completely useless (in terms of preventing releases). The time of failure would be specified by the user and could optionally be time distributed for each particular container design. Partial failure of individual containers may be justifiable under certain conditions, but is generally not recommended.

Gaseous radionuclides would be available for release immediately and completely on breach of the container. The most conservative model would assume that all HICs and liners simultaneously fail, resulting in a puff release. Iterations could be used to incorporate more realistic assumptions into the model, if gaseous pathways are proven problematic by the initial, conservative analysis.

E.4.4 Waste Form

The physicochemical properties of the waste form, once the container degrades, will determine the aqueous release mechanism(s) for the given radionuclide inventory. Gaseous release (for those waste streams with a gaseous component) would be governed by container lifetime and design (e.g., vents could allow gas to diffuse out). Following the iterative nature of performance assessment, during the initial stages of analysis, it would be beneficial to employ a few simple waste forms that would be conservative and easy to analyze. Wash or rinse release models would generally be conservative in all cases; however, it may be desirable to use other models for certain waste forms. Through initial analysis, the more important nuclides could be identified, and it is possible that additional justifiable credit (i.e., some mechanism of retarding release) for the waste form(s) containing these nuclides, could be taken.

E.4.4.1 Issues

The minimum requirements that all waste forms must meet to be acceptable for near-surface disposal are given in §§ 61.56(a). In addition to these minimum requirements, Class B and Class C wastes must meet the requirements of §§ 61.56(b), including the requirement for structural stability. Structural stability is defined in terms of ability to keep dimensions and form under disposal conditions. Structural stability can be provided by the waste form itself (e.g., cement stabilization), an HIC, or by the disposal unit itself (e.g., vault disposal). Note that structural stability does not imply that the waste form will not release radionuclides to its environment, or that it or its container is water-impermeable for the same length of time that it is structurally stable. If such assumptions are used in a performance assessment, to delay releases, they would need sufficient justification.

The different, less stringent requirements for Class A wastes result in different waste forms and suggest that these wastes may be treated separately in the analyses. Class A waste is primarily dry, compacted solids consisting of lab trash, clothing, plastics, wood, and glass. Little research has been performed on the release mechanisms that these waste forms exhibit, and a rinse-release model, controlled by solubility limits, may be entirely appropriate for them. Some Class A waste may exist in other forms, such as cement-solidified monoliths. If these wastes meet the requirements of §§ 61.56(b), they can be disposed of with Classes B and C wastes, and could be treated as such in the performance assessment; generally however, the economics of disposal prevent this. Class A disposal units therefore could contain a small component that is governed by other than rinse release.

Class B waste, by definition, consists of only short-lived radionuclides, but may contain some long-lived radionuclides in Class A concentrations. Class C waste, which will be the most hazardous waste at the site, consists of both short- and long-lived radionuclides and requires additional measures (e.g., deeper disposal depth) over Classes A or B wastes, to protect the inadvertent intruder. Since the requirements for Class B and Class C wastes are identical, except for intruder barriers, it may be appropriate to consider these waste streams together in the performance assessment. The physicochemical forms that Classes B and C waste take consist of primarily activated metals or filters, washes, sludges, evaporator bottoms, or wet solids (including ion-exchange resins) that need to be processed before disposal. Typical processing involves solidification (into cement, polymer, or asphalt) or dewatering and placement into an HIC.

With several waste forms in Classes B and C waste, it is difficult to fully characterize the release mechanisms that will determine the facility performance. However, generally more is known about the releases of radionuclides for Classes B and C waste forms than for Class A, particularly for solidified waste streams. For solidified waste forms, diffusion, as quantified by the American National Standards Institute/American Nuclear Society (ANSI/ANS) 16.1 leach test (ANSI/ANS, 1986) has been accepted as the controlling process. It is reasonable to model the release of activated metals through corrosion rates, assuming congruent dissolution and constant corrosion rates. The remainder of the waste could be conservatively modeled by a rinse release beginning at the time of container failure.

E.4.4.2 Approach

The rinse-release model is obviously too conservative for several waste form types. Some radionuclides would not be available for release until a chemical reaction occurs. Two examples would be ion-exchange resins and activated metals. Ion-exchange resins were selected by industry because of their sorption properties, and they probably wouldn't freely release all their sorbed nuclei at once (i.e., in a rinse release). However, little is known about the release of nuclei from these materials over long timeframes, in a setting such as an LLW disposal site. Thus, to take credit for some kind of partitioning properties for the resins, while seemingly reasonable, would be highly uncertain without specific experimental and site-specific geochemical data. Activated metal radionuclides would not be available for dissolution until corrosion of the metal occurs.

Release of radionuclides should be restricted such that the solubility limits are not exceeded. Because of the complex and transient nature of disposal site chemistry, obtaining reliable solubility limits is difficult and uncertainties must be addressed. Selection of the limits must be conservative under all potential conditions and is discussed in Section E.4.5, below.

Release of radionuclides from particular waste forms may be governed by more than one release mechanism. An example would be cement-solidified filter media. Typical filter media would include radionuclides in insoluble oxides, and a chemical reaction would be necessary to make the nuclide soluble. Once soluble, the release may be slowed by diffusion through the cement waste form.

The presence of several waste forms in individual disposal units will add a high degree of complication to the model, unless the waste streams and inventory are available for each form, and simplifying assumptions are made. Homogenization of the disposal unit, by allowing for percentage releases by the various mechanisms, should be performed based on site-specific information and mechanistic approaches. However, the stratification of waste form, (i.e., Class C on the bottom, with Class B and/or activated metals above it), could result in inhomogeneities that make the source term more difficult to model.

E.4.4.3 Source Term Codes

To account for the system's complexity, a mechanistic, as opposed to a generic, code can be used in source term modeling. However, both generic and site-specific information may be required for assigning parametric values within the code. A variety of source term models and codes have been developed in recent years and for comparison and discussion of different source term codes available, see the following references (Kozak, et al., 1990a, 1989a, 1989b; Sullivan, 1991; and Kozak, et al., 1993). Examples of mechanistic codes include the BLT (Breach, Leach, and Transport) and the DUST (Disposal Unit Source Term) codes developed for NRC by Brookhaven National Laboratory (Sullivan and Suen, 1989; and Sullivan, 1993). In addition, recent improvements to the NEFTRAN (NETwork Flow and TRANsport) code (Olague, et al., 1991) addresses earlier concerns (e.g., Kozak, et al., 1989b) and NEFTRAN-II is a suitable source term code when it is combined with appropriate mechanistic release algorithms for container degradation and waste form leaching.

It is important to note that the codes discussed, in both this section and in the geochemical modeling Section (E.4.5.3.3), are mentioned as examples and are not necessarily endorsed by the NRC staff. As noted previously in this technical position (Sections B.2.1, C.2.2, and D.4.2.1), it is the responsibility of the applicant to establish a rigorous quality assurance program, to ensure that codes and data bases are used appropriately in the analysis, and to provide proper verification and documentation.

E.4.5 Chemical Environment

The chemical environment within the waste disposal facility may have significant impacts on the releases of radionuclides from the waste and subsequent transport out of the disposal unit. Consideration of this chemical environment is important for two specific areas within the source term model: (1) if credit is being taken for solubility limits of radionuclide species in the aqueous phase; and (2) if credit is being taken for retardation coefficients specific to the materials within the disposal units. An understanding of the chemical environment within the disposal units is also important if the source term model is based on empirically derived radionuclide release rates or mechanisms from laboratory or field studies. Another important consideration is that a disposal system could be engineered to have specific chemical properties that will buffer the overall chemical state of the system and generate facility-specific radionuclide solubilities and retardation coefficients to be employed in the performance assessment.

E.4.5.1 Considerations and Issues

Application of source term modeling to performance assessments of engineered facilities suffers from a lack of knowledge of the chemical conditions that might occur inside a concrete vault disposal facility. In particular, the physical and chemical effects of a vault system, with large amounts of concrete present, may have a large impact on parameters that control the mobility of specific radionuclides (e.g., pH, alkalinity, ionic strength, oxidation/reduction potential, moisture content, etc.). In addition, geochemical modeling of LLW facilities involves a large number of variables and significant uncertainty. It is important to better constrain this uncertainty, which has an important effect on source term release models.

Chemical considerations that are important for assessing the releases of radionuclides from the LLW disposal facility include: (1) chemical conditions inside the disposal units that could affect solubilities, diffusion, corrosion rates, and sorption properties of radionuclides (e.g., pH, redox potential, ionic strength, buffer capacity, chemical composition, speciation, complexation, etc.); and (2) potential chemical changes (e.g., oxidizing to reducing conditions) over time, that could affect releases of long-lived radionuclides.

One key issue is to develop an understanding of the chemical environment that may occur in the disposal units to make reasonable and conservative assumptions with respect to solubility limits or retardation coefficients for the backfill material. Many source term models use these parameters, either directly or indirectly, in calculating potential radionuclide releases. The geochemical environment at different points within a disposal unit could be highly uncertain, over the performance period, because of the heterogeneous nature of LLW. However, a concrete vault disposal system is likely to contain large amounts of calcium hydroxide and calcium silicate mineral phases in various components of the system (e.g., cement waste forms, concrete overpacks, grout backfill, and the structure itself). These will likely have a strong buffering effect on the overall chemical state of the system. Thus, certain assumptions about the applicability of specific solubility limits and/or retardation coefficients will, in all probability, be appropriate in a performance assessment for such a system.

A second key issue is the applicability to vault systems of existing data on solid phase/aqueous phase partition coefficients derived from existing field and laboratory studies. This is important, because most States and compacts are developing concrete vault disposal facilities rather than trench disposal facilities. Geochemical field, laboratory, and modeling studies, that have been carried out for LLW trench disposal sites, show that, in general, the leachate solutions are reduced relative to ambient ground water, and that significant increases in major ion concentrations, and dissolved organic species occur (Serne, et al., 1990, and references therein). A better understanding of the potential chemical conditions that may exist in a concrete vault will help determine if empirically based release models derived from studies of: (1) trench systems; or (2) field lysimeter studies; and/or (3) laboratory leaching experiments are conservative for a performance assessment of a concrete vault system.

Empirical release models based upon partition coefficients derived from trench disposal systems may not be appropriate for concrete vault systems. The DEIS for Part 61 (NRC, 1981) used release factors (i.e., partition coefficients) based on ratios of measured radionuclide leachate concentrations to estimated radionuclide inventories in disposal trenches at Maxey Flats (MF), KY, (for ^{3}H, ^{60}Co, ^{90}Sr, ^{137}Cs, $^{238/239}$Pu and ^{241}Am) and West Valley (WV), NY, (for ^{14}C and ^{238}U) (Oztunali, et al., 1981). The use of the MF/WV partition coefficients implies a certain set of chemical conditions, for the disposal units, that must be justified in terms of conditions that are likely to occur in a concrete vault system. The MF/WV trench leachates are near neutral in pH and are strongly anoxic, resulting in the leachates being supersaturated with respect to certain carbonate and sulfide phases (Dayal, et al., 1986, Weiss and Colombo, 1980). Thus, if these systems have achieved a state of equilibrium then the concentrations of radionuclides, in the leachate solution, represent both mobilization from the waste forms and removal from solution (e.g., by sorption, as precipitates and co-precipitates) to secondary solid phases. A different set of chemical conditions or waste concentrations may result in significantly different equilibrium concentrations of radionuclides in solution than would be predicted from the ratios. For example, the trench leachate concentrations of ^{238}U at WV are consistent with U(IV) solubilities in a reducing environment. If it is likely that oxidizing conditions will eventually prevail in a proposed disposal system, then the MF/WV partition coefficients are not appropriate, because the solubilities of U(VI) are several orders of magnitude higher than for U(IV). Similar arguments apply to other radionuclides that are relatively immobile under reducing conditions, but relatively mobile under oxidizing conditions.

Another related problem is that the MF/WV partition coefficients for certain radionuclides are derived from other radionuclides. Thus, ^{129}I and ^{99}Tc ratios are assumed to be 10 percent of the ^{3}H ratio, Ni and Fe are assumed to be the same as Co, Nb is assumed to be 75 percent of Co, and Np and Cm are assumed to be the same as for Pu. The applicant would have to justify these assumptions and show that they are appropriate and conservative for the potential chemical conditions inside the proposed disposal units.

A more critical and fundamental problem, with using the MF/WV partition coefficients for calculating releases, is that the true waste inventories in the trenches are considerably uncertain. Moreover, for ^{238}U, the partition coefficient is derived from WV leachates and MF waste inventories. If the waste inventories for particular radionuclides are overestimated, then the partition coefficients may be underestimated, potentially by large amounts. Therefore, even if the chemical environment issues discussed above can be resolved, the use of the MF/WV ratios presupposes a knowledge base about the solid waste radionuclide inventories that cannot be supported.

A third key issue is to determine if certain materials, such as a specialized backfill or special concrete formulations, can be used to chemically condition the environment within disposal units. The goal in such an approach would be to chemically engineer the system to have certain specific properties that limit the potential mobility of particular radionuclides.

E.4.5.2 Approach

Initial analysis should make use of simple models and assumptions before implementing more sophisticated techniques. Conservative solubility limits could be set within reasonable bounds, given some consideration to geochemical factors such as pH. After initial calculations, it might prove useful to examine in further detail the chemical conditions of the system (e.g., redox state, chemical composition and ionic strength of water) to better understand the influence on solubility limits, corrosion rates, and release rates.

The following technical approaches are acceptable for treating chemical characteristics in LLW performance assessments:

1. A rinse-release model is used and no credit is taken for engineered controls on chemical characteristics including backfill, chemical barriers, and geochemistry considerations. This is the most conservative approach.

2. Credit is taken for the geochemical conditions of inside the disposal units to justify specific solubility limits, retardation coefficients, and corrosion rates. Sufficient justification must be presented for specific chemical conditions (e.g., redox conditions, pH). The justification maybe based on experimental data, and/or the use of field data, where appropriate, in conjunction with geochemical modeling.

3. If backfill materials or chemical barriers are used to retard the release of radionuclides to the ground water, sufficient justification must be provided that the sorptive properties of the material would be obtained within the chemical environment for the disposal facility. Site-specific data on backfill materials obtained from site excavations should also be presented. The justification may be based on the distribution coefficient approach, experimental studies such as field lysimeter investigations, and laboratory studies, combined with geochemical modeling.

E.4.5.3 Development of Site-Specific Parameters and Models

There are several issues and concerns that need to be addressed in developing site-specific values and geochemical models for use in the source term analysis. Similar considerations also apply to developing site-specific K_ds and geochemical models for input to the ground-water transport analysis. Of particular importance, for the latter, are the conditions and properties and models of the geologic strata most likely to be involved in radionuclide transport, to the maximally exposed individual.

E.4.5.3.1 Radionuclide Distribution Coefficients

If credit is being taken in the performance assessment for retardation coefficients in the transport of radionuclides in the backfill inside the disposal facility, then facility-specific K_ds need to be determined for the radionuclides that contribute significantly to dose (as might be shown in a preliminary screening calculation). Experiments need to be carried out to measure these specific K_ds in the site characterization phase of the program, and preliminary screening performance assessment calculations will help focus on the most important radionuclides. Representative vault water (if the anticipated chemical composition differs from that of the ground water) and representative disposal unit materials (e.g., concrete, backfill, etc.) need to be used in the experiments. A number of parameters need to be varied in the experiments, to determine, or at least bound the uncertainty, in the K_d values. These parameters are likely to be facility-dependent, but may include: time; pH; redox poise of the solution; nuclide concentration; major ion concentration and ionic strength; reduced iron content; vault-water versus ground-water chemistry; water/soil ratio; backfill and structural material variations; soil mineralogy and composition (e.g., clay content); batch experiments versus column experiments; and filtration method versus centrifugation. Note that similar considerations apply to developing values for ground-water transport.

E.4.5.3.3 Geochemical Modeling of LLW Disposal Facility

It is difficult to predict, a priori, what the aqueous chemistry inside a concrete vault will be, without some knowledge of the main reactive components of the disposal system. The applicant needs to develop a conceptual model of the chemical conditions inside a vault, if credit is being taken for a release model that is dependent on specific chemical conditions. For example, if the applicant wishes to take credit for specific solubility limits and/or sorption coefficients, then the values selected must be consistent with the conditions that are likely to occur in the disposal units.

As noted above, chemical conditions in concrete vaults may not be similar to trench conditions from which the leachate/solid partition coefficients were developed for the Part 61 IMPACTS analysis methodology (Oztunali and Roles, 1986). In general, if the applicant is relying on a source term model, in the performance assessment, that is based on field and/or laboratory data for radionuclide releases, then there is a need to develop sufficient justification to support the application of such data toward a specific site and facility. If the applicant is relying on a chemically engineered disposal unit, to retard specific radionuclides, then the applicant must present information and modeling results that support the designed properties of the proposed system.

Geochemical modeling of expected disposal facility chemical conditions, determination of the potential chemical state in the disposal units, and comparison with models of and data from, field and laboratory studies, can be done to build confidence in the use of specific release models. Site characterization data (e.g., water chemistry, soil and backfill chemistry, etc.: see NUREG-1200, Section 2.6) must be obtained for both the natural site and engineered facility. Geochemical calculations (e.g., speciation, solubilities, and sorption) may be carried out using presently available codes such as MINTEQ (Felmy, et al., 1984); MINTEQA2 (Allison, et al., 1991); EQ3/6 (Woolery, 1992a,b; Woolery and Daveler, 1992, and Daveler and Woolery, 1992); PHRQPITZ (Plummer, et al., 1988); and WATEQ4F (Ball and Nordstrom, 1991). All these codes exist in the public domain and have been subjected to varying degrees of review, QA/QC, and confirmation studies (for an overview, see Bassett and Melchior, 1990). The purpose of this type of modeling is to support the use of specific values and ranges of values within the performance assessment source term model. Although certain codes have recently been developed that couple geochemical calculations and transport (for example, Yeh and Tripathi, 1991; Schramke, et al., 1992), it is probably not necessary to incorporate a geochemical code into the source term part of the integrated systems code, unless there are compelling reasons to do so.

It is the responsibility of the applicant to ensure that the codes are being applied appropriately and that the constraints and limitations, of the codes(s) and the thermodynamic data bases employed, are carefully considered. As discussed in NUREG-1200, Section 2.6, the regulatory review process would include: (1) independently determining that the conceptual models and computer codes are used appropriately; (2) comparing the data bases used in the codes with established and up-to-date compilations; (3) determining that the input data are consistent and complete with respect to site characterization and related laboratory and field experiments; (4) determining that the interpretations of results are consistent with the data; and (5) ensuring that verification and validation of the codes are sufficient in accord with the approach discussed in Section D.4.2.1.

E.4.6 Gaseous Releases

Some of the radionuclides present in LLW can be released from the LLW disposal facility in the gas phase. For a below ground vault (BGV), advective and diffusive migration to the ground surface and subsequent transport in the atmosphere, to locations downwind from the disposal facility, may conceivably contribute a non-trivial fraction of the annual effective dose commitment, for the maximally exposed individual.

E.4.6.1 Considerations

The most important radionuclides that should be considered and evaluated for gaseous release include: ^{14}C, ^{85}Kr, ^{222}Rn, and ^{3}H. These four radionuclides may be present in LLW facilities in a variety of waste streams and waste forms. Carbon-14 is expected to be present in dry solids, dry active waste (DAW), sorbed aqueous liquids, activated metals, and animal carcasses (Gruhlke, et al., 1986). Tritium is expected to be present in dry solids, DAW, sorbed liquids, oils, and animal carcasses. Both ^{14}C and ^{3}H could be released in the gaseous phase by several mechanisms, including: (1) microbial degradation of specific waste streams; (2) changes in oxidation/reduction conditions, within the disposal facility, over time; or (3) by leaching and volatilization mechanisms involving varying pH and other water chemistry considerations. Krypton-85 is disposed of as gas in sealed containers that will degrade over time. Radon-222, having a half life of only 3.8 days, is present in the disposal facility as a daughter product of ^{226}Ra ($t_{1/2}$ = 1760 y). The latter is present both from disposal of waste containing ^{226}Ra, and from the decay of ^{238}U in LLW.

E.4.6.2 Approach

A tiered approach is recommended to determine if gaseous release, of the radionuclides ^{14}C, ^{85}Kr, ^{222}Rn, and ^{3}H in the disposal facility inventory, might contribute significantly to the effective dose commitment for the maximally exposed individual. The tiered approach starts with a screening method and progresses to more sophisticated modeling, requiring additional data, only if needed. The screening approach would assume the entire inventory of ^{14}C, ^{3}H,

^{85}Kr, and ^{222}Rn, in the disposal facility, is available for release in the gaseous phase to the surface, in a short period of time, that conservatively bounds the problem (e.g., one year). If ^{14}C and ^{3}H appear to be important contributors to the total dose commitment of individuals, it may be possible to estimate the fractions of ^{14}C and ^{3}H in LLW that is released through the gaseous pathways relative to the total inventories of these radionuclides. If the calculated dose, from these radionuclides is less than 1 percent of the Part 61 dose requirements, then no further consideration need be given, in a performance assessment, to gaseous radionuclide releases.

The applicant needs to recognize that the screening approach, described above, does not address the ground-water transport pathway. The entire inventory of the four radionuclides above would still have to be considered available for release into the ground water. A realistic and defensible generation rate and partitioning of gaseous and aqueous species for these radionuclides would have to be justified if the applicant desires to take credit for the release of gaseous radionuclides as a means of reducing the inventory that will be released into the ground water (see Section E.5.1.4).

If needed, more realistic release rates, for the four radionuclides noted above, might be based on actual gaseous release data for the WV LLW disposal site (e.g., see Matuszek, 1982; Matuszek and Robinson, 1983; and Kunz, 1982). For the purposes of doing such a calculation, a number of assumptions must be made. It is assumed that the anaerobic, reducing conditions and gas generation processes at the WV trenches (Francis, et al., 1980; Kunz, 1982; Dayal, et al., 1986) are conservative relative to the chemical conditions and chemical forms of the radionuclides that may occur in vault disposal units. Although partitioning of radionuclides between air and water is not explicitly considered, it is assumed that the release rates based on the West Valley trench data implicitly take this into account. It is also assumed that the release rates for WV (Kunz, 1982), represent a conservative estimate of release for a concrete vault disposal system. This assumption may be reasonable, given the significant differences in waste disposal practices, the forms and types of waste disposed of, and the fully saturated conditions of the WV trenches, relative to facilities proposed by various States and compacts. Nevertheless, the applicant would have to justify all the assumptions used in such an analysis.

More complicated analysis may include: determining radionuclide gaseous production rates by waste class, waste stream, and waste form from the LLW inventory; consideration of different mechanisms influencing gaseous releases (e.g., aerobic and anaerobic microbial degradation of organics, radiolytic generation of gasses); and partitioning of the radioactive gases between the aqueous and gas phases (Yim, et al., 1993). In a concrete vault disposal system with a large amount of internal concrete (e.g., in overpacks, grout backfill, and so forth), the applicant may need to consider the effects of the high pH and large amounts of calcium (Ca) present to take credit for the precipitation $^{14}CO_3^{=}$ as calcium carbonate ($CaCO_3$).

E.5 Transport Media

E.5.1 Ground Water

E.5.1.2 Objective

The objective of the ground-water flow and transport analysis is to assess the ground-water contribution to the annual dose encountered by the maximally exposed member of the general population. This objective has two elements that help focus the analysis:

(1) The reference to the maximally exposed member of the general population implies that the maximum applies over the entire time domain of interest and over the entire spatial domain that might be inhabited by a member of the general population. The region of consideration is commonly inferred to represent the region external to the disposal site boundary.

(2) The assessment of annual dose requires an integration of dose over time for a period of 1 year, rather than a dose rate derived from radionuclide concentrations at specific times.

E.5.1.3 Key Considerations in the Analysis

Two key considerations in the ground-water flow and transport analysis relate to the following: conceptual model development, and identification of receptor locations. A brief discussion of these considerations follows, followed by a discussion of a recommended approach to address them.

Geologic systems, by their very nature, are complex, three-dimensional, heterogeneous, and often anisotropic. Analysts will never have quite enough hydrogeologic data available to uniquely define, within the analysis, all the variability in the hydrologic properties of the hydrogeologic system; therefore, assumptions and approximations will have to be made. A conceptual model of a real system is obtained by making simplifying assumptions that reduce the completeness and complexity and time dependence of the real system, while still retaining the salient features and processes most relevant to the problem.

The main components of a site-specific conceptual model of a hydrogeologic system include structure, processes, and boundary conditions (Bergeron and Kincaid, 1991). Structure defines the geometry of the system as determined by stratigraphy, faults, heterogeneity, and other geologic characteristics. Processes are the physical and chemical phenomena affecting flow and transport. Hydrologic processes may include: advection, dispersion, and diffusion. Geochemical processes may include: sorption, precipitation, complexation, and redox reactions.

An important consideration is the definition of the site-specific features and processes of the hydrogeologic system. The quantification of these features need to be included in the analysis. The determination of which processes and features to consider will have to be based upon what is needed to demonstrate compliance with the performance objectives. The analyst will have to decide how best to synthesize site characterization data into a relevant representation of the hydrogeologic system. This means determining how to represent the various stratigraphic units into hydrostratigraphic units and then to determine which of these hydrostratigraphic units need to be included within the analysis. Further, the analyst will have to decide whether the hydrostratigraphic units can be grouped so as to simplify the analysis. Although advection will be the predominant means of transport for most cases, the analyst will have to consider the importance of accounting for dispersion. Over the scale of the analysis, dispersion may not be very important. Determining the influence of some of the geochemical processes may be extremely difficult; therefore, their importance to demonstrating compliance with the performance objectives will have to be weighed.

Once the analyst has determined the appropriate features and processes to include within the analysis, some consideration must be given to the appropriate dimensional representation to include. For example, it is possible to analyze contaminant transport in a one-dimensional flow field and still account for three-dimensional dispersion; however, the analyst will have to consider how important three-dimensional dispersion is to demonstrating compliance with the dose requirements, since dispersivity values are difficult to obtain.

The analyst will also have to determine how best to represent the spatial variation of hydrologic parameters used to characterize features and processes included within the analysis. Although a given value for a particular parameter may appear to be conservative, the effect of that particular parameter, on the calculated dose, is difficult to determine a priori. For example, selecting a high hydraulic conductivity for the ground-water system may appear conservative in terms of increasing the rate of contaminant transport, but may not be conservative in terms of the dose calculation, because of increased dilution.

Another key consideration concerns the receptor location. In assessing the dose to the maximally exposed member of the general population, the analyst will have to consider radionuclide concentrations in ground water at all potential points down-gradient from the disposal unit where a human could come into contact with the contaminated water. This means that both real and hypothetical ground-water discharge points will have to be considered. Such discharge points could include streams, wells, springs, and seeps. An analysis based solely on existing (i.e., real) discharge points will likely be non-conservative since, over the long timeframes covered by the analysis, additional human access locations may develop closer to the disposal unit. Therefore, the analysis will likely involve a hypothetical well, and the analyst will have to make some assumptions in terms of where to assume that the well is located. In addition, the analyst will have to make assumptions regarding the well construction. Design features, such as well depth and screen length, are important in terms of determining how much water is available for dilution and how much of the plume will be captured by the well.

In the previous discussions, it was assumed that transport in the ground-water system would be in the liquid phase. However, transport of the gaseous radionuclides through the ground-water system may also need to be assessed, if initial air transport screening and bounding calculations, or other more complicated screening models fail to demonstrate that the dose contribution from the air pathway is insignificant. In considering air transport through the ground-water system, the air-phase dynamics may need to be considered, since the gaseous contaminants move through the air-filled pores in the unsaturated units overlying the LLW disposal cells.

E.5.1.4 Approach

Figure 11 shows an approach recommended by the NRC staff for the performance assessment ground-water flow and transport analysis. The first step in the analysis is to develop a conceptual model of the hydrogeologic setting. The site characterization should provide the basis for the conceptual model. Additional auxiliary analyses may be useful in identifying important processes to be considered in the conceptual model and filling in data gaps.

Because the purpose of the performance assessment analysis is to determine compliance with a standard, as opposed to predicting actual doses, it may be possible to greatly simplify the conceptual model for the sole purpose of demonstrating compliance. Therefore, the NRC staff recommends that initial conceptual models be kept simple. More details can be included, as needed, for the purpose of demonstrating compliance with the performance objective. As indicated in Section C.2, it is very likely that several potentially credible conceptual models may be developed, especially during the early stages of the site characterization and performance assessment analysis, when data may be limited. Therefore, keeping the analysis simple will help facilitate analyzing all credible conceptual models.

Since the analysis will calculate the dose to the maximally exposed member of the general population, the analysis needs to provide concentrations in well water at a location on the site boundary that would have the highest composite concentration of radionuclides.
For conservatism, the analyst should consider all points on the disposal site boundary as potential well locations. The analyst can assume that the well is designed, in terms of depth and screen length, with characteristics common to the region in which the site is located. The analyst should treat the well as a pumping well (as opposed to a monitor well); therefore, its capture zone should be assumed to be at steady state conditions. This assumption means that the capture zone will extend indefinitely in the direction of the plume. As a result, any contaminant within the capture zone will eventually reach the well.

Again, because the well is treated as a pumping well, the analyst should assume that the well will pump enough water to provide the annual water requirements of a hypothetical user. The amount of water assumed to be pumped from the well should coincide with the water requirements assumed as part of the overall dose analysis. For example, if the well is assumed to supply water for irrigation and drinking, the amount of water assumed to be pumped should be that needed to meet these two requirements. Concentrations should represent the average concentrations in water pumped from a well over the course of a year, not concentrations at an instant in time.

As an approach to the simulation of radionuclide transport within the ground-water system, the NRC staff recommends an analysis for each discrete source (i.e., disposal unit) using a

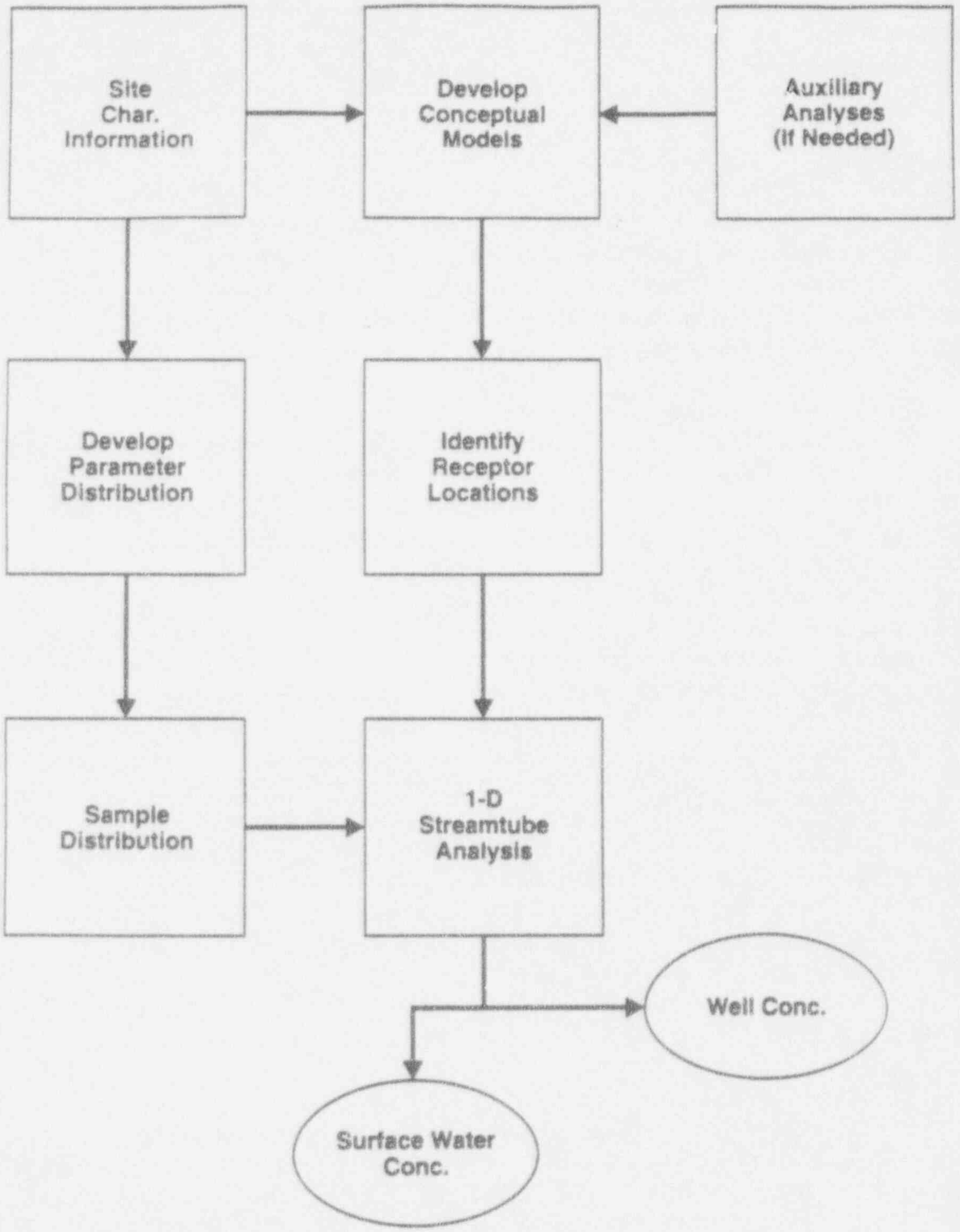


Figure 11. Approach to ground-water flow and transport analysis.

connected series of one-dimensional streamtubes from the source area to the water table, then to the well, and possibly to any location where ground water discharges to surface water. As an example, Figure 12 depicts a cross-sectional slice through a hypothetical disposal system and hydrogeologic environment, including a well. The streamtube associated with a vault consists of a vertical segment from the vault to the water table. The streamtube connects to a segment that crosses aquifer zone 1 and then connects to a section within aquifer zone 2. The streamtube should more-or-less correspond with the direction of regional ground-water flow. In this diagram, one streamtube is fully intercepted by the pumping well. Within a one-dimensional streamtube, solute transport is modeled to consist of advection with the moving water and dispersion in the direction of flow. Typically, the analysis should account for radioactive decay, possibly with daughter in-growth.

The bases for the identification and approximation of the location and properties of the one-dimensional streamtube segments are auxiliary analyses of the ground-water flow system at the site. The analyst can establish the geometry of the streamtube, using the geometry of the disposal unit(s), while maintaining continuity. The source term can be assumed to be diluted by the volume of clean ground water within the streamtube.The approximation of transport through one-dimensional streamtubes ignores the reduction in the concentration of radionuclides due to dispersion normal to the flow direction (also called transverse dispersion). The limited distance between the radionuclide source and the well reduces the significance of transverse dispersion, in general. Because the analysis is aimed at evaluating the concentration of radionuclides in water discharged by a well, rather than the distribution of concentration within a ground-water flow field, transverse dispersion has even lesser significance. A well withdrawing ground water modifies the natural ground-water flow field by inducing flow to converge toward the well. Flow captured by the well may consist of both uncontaminated water and a segment of a plume contaminated with radionuclides. The concentration of radionuclides in water discharged by the well would therefore be reduced by the dilution provided by the uncontaminated water. Proper consideration of the influence of the pumping well is essential for the reasonable approximation of concentrations of radionuclides in water pumped from the well.

The extent of the streamtube associated with a contaminant source can be envisioned by tracing flowlines or streamlines emanating from the source and evolving with the velocity of the ground-water flow system. As the flowlines approach the well, some flowlines may be intercepted by the well, while others bypass the well, more or less following the regional-flow field. Those flowlines that are intercepted by the well form the extent of the streamtube to be considered during the transport analysis from the source to the well. In the event of multiple discrete sources, multiple iterations of similar analyses can be used to prescribe the appropriate streamtubes.

Although the streamtube analyses will provide approximations to radionuclide concentrations in ground water adjacent to the well, supplemental analyses must be conducted to estimate the contribution of radionuclides derived from the total volume of water withdrawn by the well. In other words, the well averages the concentration, based on the proportion of contaminated and uncontaminated water pumped. If an analyst were to account for transverse dispersion in the approximation of contaminant transport to the well, the well

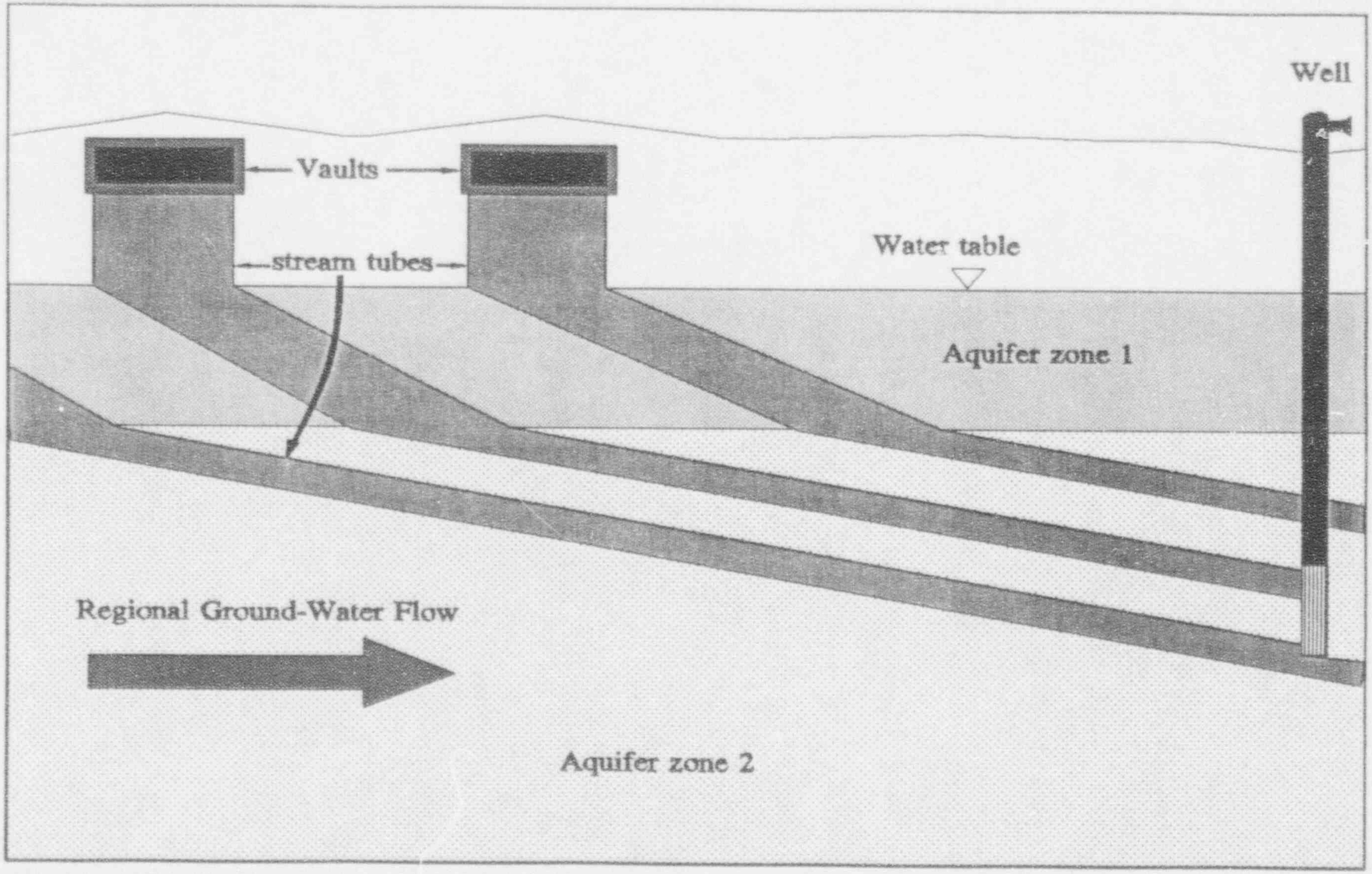


Figure 12. Schematic of streamtube conceptualization.

would "average" the concentration of water with varying amounts of contamination, rather than averaging concentrations from contaminated and uncontaminated streamtubes.

Processes and mechanisms that delay the transport of radionuclides will, in most cases, have minimal effect in reducing doses from long-lived radionuclides, because of their long half-life and the short travel distance. The analyst may consider the potential for retardation of some of the key short-lived radionuclides. For the most part, radioactive decay of the short-lived radionuclides can be achieved before they leave the disposal unit; therefore, their decay through the ground-water pathway should have minimal effect in reducing doses. Because of the important effect of pH, organic content, soil texture and mineralogy, and other soil characteristics on distribution coefficients, site-specific distribution coefficients should be used in the analysis (see Section E.4.5.3.1 - "Distribution Coefficients"). Geochemical processes, especially those that permanently remove contaminants from ground water (e.g., irreversible sorption, precipitation, etc.) may provide additional means of reducing the ground-water concentrations at the hypothetical well. In general, to account for such processes within the performance assessment analysis will require auxiliary geochemical analyses (see Section E.4.5.3.2). It is recommended that the analyst not include such processes in initial analyses, because they may not be needed to demonstrate compliance with the dose requirements.

Since the performance assessment calculations will cover a long period of time, the analyst can assume that the flow field is at steady-state. For most cases, this should be an appropriate assumption, because seasonal or annual variations in hydrology are not expected to contribute greatly to the overall performance of the site (Kozak, et al., 1989a). Because of variability in hydrologic properties, hydrologic parameters used in the analysis should be statistically sampled, based on their assumed distributions.

For sites with a relatively thin unsaturated zone beneath the disposal unit, travel time from the vault to the water table will not afford a significant amount of radioactive decay. Therefore, for sites with shallow water tables, the analyst may neglect transport through the unsaturated zone. For sites with deep water tables, appreciable radioactive decay can occur, as the radionuclides are transported through the unsaturated zone. For these cases, the analyst may approximate the transport through the unsaturated zone by applying a simple delay time (and a corresponding radioactive decay and potential daughter in-growth) based on an appropriate estimate of travel time for this radionuclide, over this segment of the unsaturated zone.

The recommended approach for assessing gaseous radionuclide transport through the ground-water system is to begin with simple bounding calculations, that allow a significant percentage of the available vapor inventory to be released to the surface. If this approach cannot demonstrate compliance, then more detailed analyses may be warranted. These approaches would include consideration of controlling features, such as pneumatic properties of the engineered and natural materials, that vary as a function of moisture content and pressure gradients. Coincident infiltration and air movement conditions need to be determined for these more detailed models.

The effects of infiltration and transient moisture content movement create great uncertainties and complexities, when formulating a ventilation transport model (Sweed, Binning, and Celia, 1992). Ideally, simultaneous vapor and solute transport modeling could be conducted using numerical simulators such as those described by Sweed, Binning, and Celia (1992) and Celia and Binning (1992). An important observation in modeling air-phase flow and transport is the importance of establishing the boundary conditions which control the air flow direction and velocity field variations (Celia and Binning, 1992).

Use of these detailed vapor-phase transport approaches account for both the vapor and dissolved liquid phases, thus avoiding double counting and incompatible transport scenarios (i.e., low infiltration fluxes resulting in high vapor fluxes rather than high infiltration fluxes causing high liquid transport fluxes). Justification for the definition of these processes and parameter identification in the performance assessment models must be provided by the licensee.

E.5.2 Surface Water

E.5.2.1 Objective

The objective of the surface-water transport analysis is to assess the surface-water contribution to the annual dose encountered by the maximally exposed member of the general population. Surface-water dose scenarios should be consistent with the exposure scenarios considered in assessing the ground-water pathway. For example, it may not be necessary to evaluate doses from consuming surface water for domestic use, when ground water is shown to be the principal domestic water-use pathway for the disposal site. As in assessing doses for the ground-water pathway, the maximally exposed individual is a member of the general population residing at or near the site boundary.

E.5.2.2 Considerations

Surface-water bodies can become contaminated with radioactivity from the direct mobilization of contaminants by overland flow crossing a disposal site or by inflow from seeps and springs that are contaminated with leachate percolating from an LLW disposal facility (see Figure 13). For radionuclide transfer overland, contaminated runoff entering a stream may undergo dilution immediately, but radionuclides that have been deposited on the ground may subsequently become incorporated into plant or animal tissue, or become subject to further downstream transport, through successive episodes of erosion and deposition. The transfer of radionuclides via overland flow is generally not considered to be significant to the performance of BGV disposal facilities constructed according to Part 61 requirements.

In surface water, radionuclides can occur in either the water column or in the sediment. Partitioning among forms that remain in either solution or suspension, or that settle to the bottom, is controlled by the geochemical environment of the surface-water body. Radionuclide concentrations in water normally will be reduced by continued dilution with non-contaminated water or by adsorption onto bottom sediment.

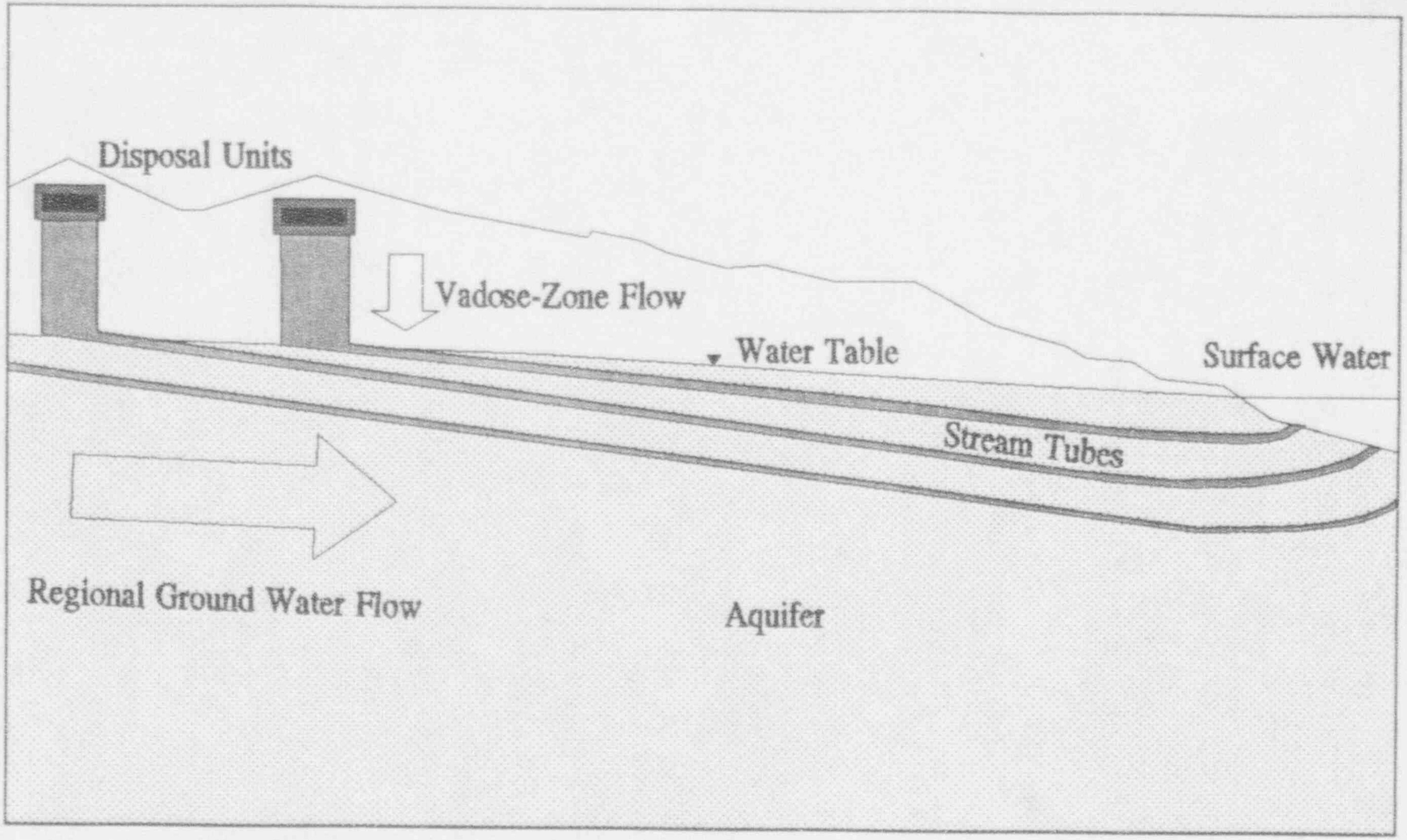


Figure 13. Conceptualization of surface water contamination pathway.

Note that all radionuclides distributed in the aquifer in the vicinity of the surface-water body are discharged into it.

When a tributary stream joins a larger stream, mixing is not always instantly complete. Often, the water from the influent stream flows unmixed for miles alongside water in the major stream, until dispersion, diffusion and turbulence cause the waters to mix. When the influent stream is contaminated with radioactivity, the level of specific activity is not fully diluted until mixing is complete. Therefore, in assessing doses that result from consuming drinking water withdrawn from a surface stream, an assumption that complete mixing has occurred may not be conservative.

Instantaneous complete mixing is also unlikely when stream flow enters a retardant body of water such as a lake, reservoir, wetland, or tidal body. Turbulence can contribute to mixing, but thermal or density stratification may instead serve to impede such mixing if the influent stream flows as a tongue along the bottom or at some elevation in the water column. Slow flushing in a wetland or a tidal water body may also serve to concentrate radionuclides; moreover, precipitation of radionuclides may occur if entry into a brackish or saline environment affects solubility. In any of these water bodies, there is likelihood that aquatic organisms, both plant and animal, will concentrate whatever radionuclides are made available to them.

Potential dose pathways for surface water analysis may include the use of surface water for domestic use and irrigation; animal husbandry, with or without bioaccumulation; water-contact activities such as recreation, when there may be direct gamma radiation from exposure to contaminated sediments; and consumption of fish taken from contaminated surface-water bodies. Concentrations of radionuclides in bottom sediments can usually be ignored. Gamma-emitting radionuclides in bottom sediments are generally incapable of producing significant doses, except possibly in low-velocity areas where sediments may accumulate, and the dose-conversion factors for eating fish implicitly account for bioaccumulation in bottom-feeding aquatic organisms. The point of exposure for the surface-water pathway will normally be at the nearest downstream location where surface-water contact or withdrawal is feasible.

It is unlikely that any surface-water pathway analysis would need to include all of the processes described above, and the technical issues that will need to be resolved depend on whether the facility is constructed above or below the ground surface. For below-ground disposal facilities (i.e., BGVs and EMCBs), eventual degradation and failure of the disposal units results in enhanced releases to ground water, but do not directly expose the waste at the surface. Above-ground disposal facilities (i.e., AGVs), however, rely entirely on their engineered barriers to isolate waste from the surface environment. Eventual degradation of the vault structure will expose the waste and subject it to redistribution by surface processes. Therefore, the modes of failure, source terms, and transport processes for AGVs may tend to elevate the significance of surface-release pathways, including surface water, to their performance, and make them potentially more complicated to analyze. In assessing the performance of a degraded AGV, it may be necessary to estimate the proportion of radionuclides released that enter the surface-water system directly from overland flow and transport, and the proportion that enters the surface-water system via ground water through seeps or springs. Depending on the individual times of travel and dilution en route, the two transfer mechanisms to surface water may each have significance for human exposure, over entirely different timeframes.

E.5.2.3 Recommended Approaches

E.5.2.3.1 Below Ground Disposal Facilities

For purposes of this guidance, an EMCB (i.e., a facility that is constructed above natural grade and mounded with earth) is considered to perform as a BGV. The most important transfer mechanism of radionuclides from a BGV to surface water is through ground-water transport from the BGV to surface seeps and springs. The interaction between the ground-water pathway and the nearby surface-water bodies needs to be assessed. The surface-water models should be based on the conservative assumption that all radionuclides distributed in the aquifer in the vicinity of the nearby surface-water body are discharged into it. The discharge should be assumed to occur at a point at the shore; a diffuse laterally distributed plume entering the surface water is less conservative.

The NRC staff recommends that a first approach to calculating surface-water concentrations involves diluting the ground-water concentration at the point of release (i.e., spring) by the ratio of the surface-water discharge to the ground-water discharge calculated from the ground-water model (see Section E.6.1) at the spring location. To calculate the radionuclide concentration and ground-water discharge rate at the spring, a one-dimensional streamtube analysis, as used to calculate ground-water concentrations at the site boundary, is recommended. It should be noted that the determined coincident streamflow and ground-water discharge should based on a common meteorological database and analysis.

If radionuclide transport away from the initial point of surface-water contamination is an important site-specific consideration in the performance assessment, the staff recommends that the next step should be use of a site specific surface-water transport model. For example, where its inherent assumptions are appropriate, the GENII model can be used for a river or lake (Napier, et al., 1988). The surface-water model within GENII assumes that the flow depth, convective velocity, river width, and lateral dispersion coefficient are constant; the river channel is straight and the point discharge of contaminants is continuous (Kozak, et al., 1990a). Other examples of analytical models used to calculate surface-water concentrations in streams subject to mixing and dispersion are provided in NRC Regulatory Guide 1.113 (NRC, 1977c); (these models are contained in the GENII computer code). These models however are for short-term transient releases and may need to be modified to consider long-term chronic contaminant releases.

The pathways usually of importance in LLW performance assessment relate only to dissolved radionuclides; consequently, radionuclide interaction with the sediments frequently is neglected, but should be justified, based on local conditions. The more usual effect of neglecting sediment sorption is to produce conservative estimates of exposure via the food chain (National Council on Radiation Protection and Measurement, 1984). A simple approach to sorption of radionuclides onto sediments is included in GENII and can be used if needed.

E.5.2.3.2 Above Ground Disposal Facilities

In conducting a performance assessment of an AGV, an applicant will be expected to address the technical concerns raised above, in Section E.5.2.2. However, the staff has not evaluated the performance of AGVs and is, therefore, unable to recommend specific approaches for addressing runoff and the distribution of radionuclides on the surface that may be of importance to assessing surface water contamination from AGVs.

E.5.3 Air Transport

E.5.3.1 Objective

Some radionuclides present in LLW could, under certain conditions, be released from a LLW disposal facility in the gas phase. Subsequent transport in the atmosphere, by dilution and advective dispersion mechanisms, to locations downwind from the burial facility, may conceivably contribute a non-trivial fraction of the effective dose commitment for the maximally exposed individual. In addition, those radionuclides released to the atmosphere could accumulate on the ground by either dry or wet deposition and become incorporated into the food-chain pathway and contribute to the total effective dose equivalent through ingestion.

The objective of the air-pathway modeling is to determine an upper bound to the total effective dose equivalent from gaseous radionuclides released to the atmosphere from LLW disposal facilities. The approach employs a screening methodology with a simple model and conservative meteorological conditions to determine if releases of gaseous radionuclides to the atmosphere would be a cause of concern. This section considers only gaseous releases from BGVs and EMCBs - particulate releases from such facilities are not considered. In addition, potential gaseous and particulate releases from AGV disposal facilities are not covered in this technical position.

E.5.3.2 Considerations

Releases of radionuclides as gases from LLW disposal facilities, and subsequent transport in the atmosphere to the maximally exposed individual, depend on a number of factors. Generally, the most important radionuclides that must be considered for gaseous source term and evaluated in the air pathway transport modeling for the LLW performance assessment are ^{14}C, ^{85}Kr, ^{222}Rn and ^{3}H, which are present in a variety of LLW streams and forms. Further details, on source term releases of gaseous radionuclides and transport to the ground surface, can be found in Sections E.4.6 and E.5.1.4, respectively, of this technical position. Atmospheric transport considerations include: (1) atmospheric plume model parameters, such as gaseous release source height (ground surface for most disposal options), wind speed, wind direction, atmospheric stability class, and annual rainfall rate; (2) radionuclide removal mechanisms (e.g., radioactive decay, and wet and dry deposition), that reduce the activity levels in the atmosphere; and (3) the general topography of the land near the disposal facility.

As the radionuclides travel from their release point, several processes could reduce their concentrations below that predicted by diffusion, alone. These removal mechanisms include radioactive decay, dry particulate deposition and wet deposition (i.e., rainfall scavenging). Most of the radionuclides of concern are assumed to be in a gaseous form (i.e. $^{14}CO_2$, $^{14}CH_4$, or HTO) or are noble gases (i.e. ^{85}Kr) and dry deposition will not occur for these species. Note that radon daughter products tend to attach to dust particles because of static charges and could undergo removal from the plume by both dry and wet deposition. At most LLW disposal facilities, rainfall is expected to occur during a small percentage of the hours in a year, so that the dose calculation, to the individual, that could be affected by wet deposition may not be significantly changed by ignoring it.

Radionuclide transport in the atmosphere is usually modeled by using such methodologies as Gaussian plume transport (Slade, 1968 and Randerson, 1984) and Pasquill-Gifford atmospheric stability parameterization (Pasquill, 1974 and Culkowski and Patterson, 1976), to determine the dispersion and diffusion factors for estimating the concentrations of radionuclides at distances downwind from the disposal facility as recommended in NRC Regulatory Guide 1.111 (NRC, 1977b), NRC Regulatory Guide 1.145 (NRC, 1982) and NUREG/CR-3332 (Brenk, et al., 1983).

Determining atmospheric transport, dispersion, and dose to the exposed individual from gaseous radionuclides released from an LLW disposal facility can be performed, by using hand calculations or with an assortment of computer codes. These approaches can be used to compute dose either in a single direction, from a point source release, or using more sophisticated models, from area releases, in a multitude of directions from the disposal facility. A summary of atmospheric transport and diffusion models, for monitoring or predicting the transport of gaseous materials, developed by federal agencies, has been prepared by the National Oceanic and Atmospheric Administration (NOAA) (DOC/NOAA, 1993). Because LLW disposal facilities occupy large areas of land, a more realistic determination of dose to the maximally exposed individual from radionuclides released to the atmosphere may be obtained by using an area or virtual point source release model instead of point source release models.

E.5.3.3 Approach

A screening approach is recommended to determine if gaseous releases of the radionuclides ^{14}C, ^{85}Kr, ^{222}Rn, and ^{3}H from the disposal facility contribute significantly to the total effective dose equivalent for the maximally exposed individual. The screening method follows a tiered approach starting with simple yet conservative method and progressing to a more sophisticated screening method relying on additional site-specific data.

E.5.3.3.1 Initial Screening Approach

Conservative gaseous radionuclide releases and meteorological conditions incorporated into standard generic atmospheric transport models may be sufficient to determine if releases of gaseous radionuclides to the atmosphere would be a significant contributor to dose. This screening approach would assume the entire inventory of available gaseous radionuclides in the disposal facility is available for release in the gaseous phase to the surface. The dose to the individual may be estimated, using a total gaseous radionuclide release over one year and reasonably conservative meteorological conditions for wind speed, atmospheric stability class, and atmospheric diffusion. If the calculated dose is less than one per cent of the Part 61 dose requirements, no further consideration need be given in the performance assessment for gaseous radionuclide releases.

A screening process is recommended that initially assumes the total radionuclide inventory of ^{14}C, ^{3}H, ^{85}Kr, and ^{222}Rn is released from the disposal facility to the surface in a one-year period. If other release rates are used that involve the entire inventory released as gaseous radionuclides over longer time periods (e.g., entire inventory released over 100 years) or involve smaller yearly release rates, justification should be provided. Radon-222 activity levels can be obtained from the ^{238}U decay series for the year, of the performance assessment, in which U daughter product activity is maximized (e.g., the 10,000th year). The chemical form of the radionuclide should be the most conservative, volatile species. Other pathways, or partitioning of radionuclides between air and water need not be considered for this screening approach.

For screening purposes, the gaseous radionuclides can be released as a point source or an area source from the disposal facility and wind directions can be either single directional, downwind from the center of the disposal facility, or multidirectional, radiating outward from the center of the disposal facility. Ground-level transport of the radionuclides can be assumed and Gaussian plume models, with Pasquill-Gifford dispersion parameters, can be used, to provide the ground-level atmospheric diffusion factor, χ/Q, for radionuclide concentrations, and doses can be calculated for the inhalation pathway, except for ^{85}Kr, where the submersion dose is the dominant pathway.

Single directional ground-level releases from a point source release along a plume centerline, or across a 22.5° wind-sector average, are acceptable for determining doses at downwind distances from the disposal facility. For single direction, air pathway calculations, the atmospheric diffusion factor, χ/Q (sec/m^3), for ground level releases, may be calculated from standard equations involving wind speed, atmospheric stability conditions, lateral plume speed, and vertical plume speed (NRC, 1977a; NRC, 1982; Brenk, et al., 1983; and Turner, 1970), or from atmospheric transport computer codes, such as DWNWKE.PC (Fields and Howe, 1993). A chronic breathing rate, inhalation dose conversion factors for ^{14}C, ^{3}H, and ^{222}Rn, and an external dose conversion factor for ^{85}Kr can be used to estimate the annual effective dose equivalent to the maximally exposed individual downwind from the disposal facility. For ^{222}Rn, a conservative estimate of 100 percent equilibrium with daughter products, is acceptable. The applicant can propose alternate equilibrium levels if they can be supported and shown to be appropriate.

Those computer models, such as PRESTO-II (Fields, et al., 1986) or PRESTO-EPA-POP (Fields, et al., 1987), which contain a Gaussian plume atmospheric transport and dispersion subroutine to calculate gaseous radionuclide transport and deposition in a direction downwind from a release point and the necessary dose parameters including inhalation dose conversion factors may be used to calculate dose directly to the maximally exposed individual.

Uniform area source releases to the atmosphere can be modeled with CAP88-PC (Parks, 1992). Inhalation dose can be estimated by CAP88-PC multidirectionally from the center of the disposal facility for the 16 compass directions (22.5-degree sectors centered on true north north-northeast, etc.) using either the weather data library in the model closest to the disposal facility or from site specific meteorological data.

No further consideration need be given in the performance assessment to gaseous radionuclides if the calculated dose is less than one percent of the Part 61 dose requirements. For those radionuclides exceeding this dose requirement, additional evaluations described below in the detailed modeling approach must be performed. The licensee must provide justification for the conservative assumptions and values used.

E.5.3.3.2 Detailed Modeling Approaches

An increasing level of detail may be required to demonstrate the performance objectives can be met for gaseous radionuclides released to the atmosphere. More complicated analysis involving the waste streams and waste forms in the disposal facility and considerations involving the transport of gaseous radionuclides through pores in the unsaturated ground water system may be needed to demonstrate compliance with Part 61 requirements. Further information, on these and other processes, can be found in the Sections E.4.6, for source term considerations, and E.5.1.4, for ground-water considerations.

This detailed modeling approach should also include more reliance on site-specific meteorological conditions, and a more thorough assessment of dose from the food-chain pathway. For example, radionuclides removed from the plume by precipitation scavenging and dry particulate deposition, may be directly taken up into the food-chain. Further information on pathway analysis can be found in Section E.6, of the technical position. Pathway modeling for the air releases is similar to ground water releases.

If the result of the more detailed analysis, using conservative site-specific data, is a dose to the maximally exposed individual of less than one percent the § 61.41 limits, no further effort is necessary to demonstrate compliance for the air pathway. The licensee must provide justification in the performance assessment of all assumptions, data, and models used by the licensee.

E.6 Dose

E.6.1 Objective

The objective of dose modeling for performance assessment is to provide estimates of potential doses to humans, in terms of the maximally exposed individual (see Section E.1), from releases of radioactivity from an LLW disposal facility, after closure. In this role, dose modeling integrates the information from the various modeling areas (see Sections E.1-5).

E.6.2 Considerations

Dose modeling for performance assessment includes the transfer of radionuclides through the human food chain and human dosimetry. The goal of this guidance is to aid in understanding important issues related to human impacts from potential releases of contaminants from an LLW disposal facility. In addition the guidance will provide some discussion of the calculations necessary to assess these potential doses.

This guidance supplements the pathway and dosimetry guidance provided in NUREG-1200, Section 6.1.6 (NRC, 1991a). That guidance, along with other generally applicable pathway identification and dose calculation recommendations referenced below, provides a broad range of considerations and background information used in the development of NRC staff experience in pathway and dose assessment.

There are two specific areas to consider in the assessment of doses to humans. First, the mechanisms of transfer through the biosphere to humans must be identified and modeled. Second, the dosimetry of the exposed individual must be modeled. Both dose models and calculations are discussed below; however, this technical position does not endorse any specific codes to be used in an LLW disposal facility performance assessment. The applicant will be responsible for providing sufficient support and documentation for codes used in a performance assessment. The applicant should be familiar with the models and methodologies and provide enough information to make an independent determination as to the adequacy of any codes used for dose modeling.

Pathway and dose assessment in performance assessment is a process that consists of more than just calculating potential dose values from environmental concentrations. The pathway and dose modeling process integrates information from other sub-modeling areas, includes biotic pathway (food chain) analyses and dose calculations, and feeds information back to this and other sub-modeling areas. This process is consistent with the iterative nature of performance assessment. In addition, the simplified models and analysis, suggested in this technical position, support iterative modeling.

As discussed above, dose modeling includes biotic pathway (food chain) analysis. This pathway analysis consists of pathway identification and pathway modeling, both of which are discussed further in this section. Pathway identification at an early stage of the iterative process is very important.

E.6.2.1 Pathway Identification and Modeling

Specific pathways to be modeled for demonstrating compliance with the performance objectives of § 61.41 are discussed in Shipers (1989) and Shipers and Harlan (1989). An example of the pathways to be considered is provided in Figure 14. Existing NRC staff guidance (NUREG-1200) states that any pathway that contributes less than 5 percent of the peak dose need not be considered in the performance assessment. This indicates, however, that the relative contribution from each possible pathway should be evaluated. Section E.6.3.1 provides a recommended approach to determine which pathways to consider.

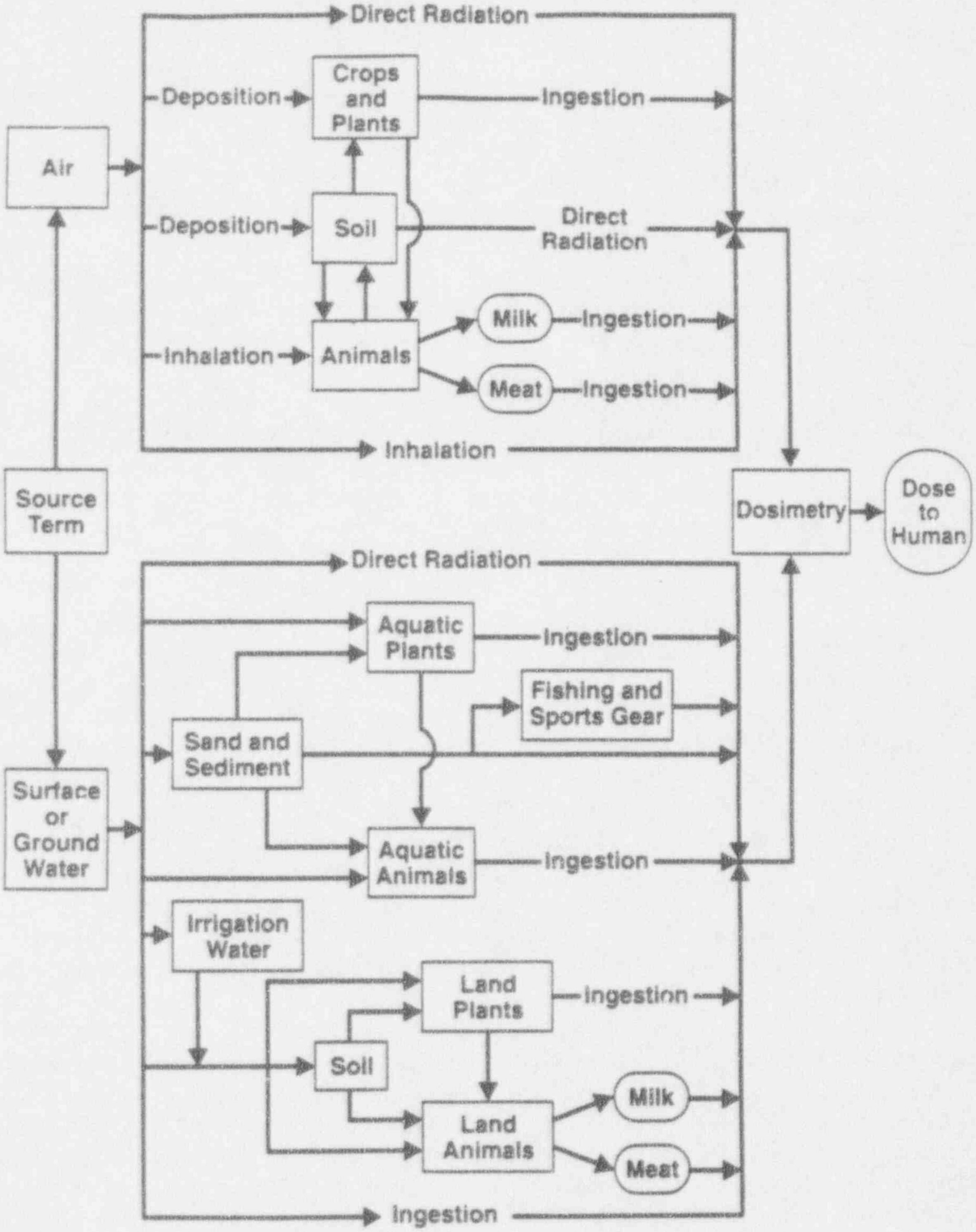


Figure 14. Potential pathways to be considered (Adapted from U.S. EPA, 1972).

Various considerations should be taken into account when modeling the transport of radionuclides through the biosphere to humans. These considerations should include:

(1) Modeling the movement of radionuclides through the food chain, adequately reflecting complex symbiotic systems and relationships;

(2) Treating certain isotopes individually (e.g., ^{14}C and ^{3}H) as their uptake behavior is different from other radionuclides;

(3) Identifying usage, production, and consumption parameters, for various food products and related systems, which may vary widely, depending on regional climate conditions, local or ethnic diet, and habits; and

(4) Assessing bioaccumulation that may reconcentrate radionuclides in the food chain. In addition to the above concerns, one must be concerned with both the complexity and conservatism of a model. Also, unique issues may emerge, based on site-specific conditions that the applicant considers in the analysis. Section E.6.3.1 provides a general approach to pathway modeling.

E.6.2.2 Internal Dosimetry

The internal dosimetry methodology used in performance assessment should be readily apparent to the reviewer. It is recommended that the methodology be consistent with the methodology used in Part 20 (effective January 1, 1994) for calculating doses to the maximally exposed individual from potential releases of radionuclides from an LLW facility. Thus, calculation of a total effective dose equivalent (TEDE), a summation of the annual external dose and the committed effective dose equivalent, is acceptable for comparison with the 0.25 mSv (25 mrem) whole body dose performance objective. Note that 0.15 mSv (15 mrem) TEDE is roughly equivalent to the 0.25 mSv (25 mrem) whole body dose for most radionuclides. Organ doses, or the committed dose equivalent, to the thyroid and the other maximally exposed organ can also be calculated, using the 10 CFR Part 20 methodology and compared with the 0.75 mSv (75 mrem) and 0.25 mSv(25 mrem) performance objectives for the thyroid and other organs, respectively.

The simplified approach of calculating doses using dose conversion factors (DCFs) will assist in conducting performance assessment. The U.S. Environmental Protection Agency (EPA) has published, in Eckerman, et al., 1988 [Federal Guidance Report (FGR) 11] DCFs for inhaled and ingested intakes of radionuclides for most isotopes. This publication provides a simple intake to dose ratio for most isotopes considered in an LLW performance assessment. Internal doses can be calculated using the internal DCFs provided by EPA in FGR 11. These DCFs represent the dose per unit intake values calculated using the methodology discussed above. The use of DCFs can be easily incorporated in the development of pathway DCFs, as discussed in the DEIS supporting Part 61 (NRC, 1981).

The influence of dose rate on dose assessment is a source of uncertainty in dose assessments using internal DCFs. Dose rate is a constant parameter; if the time of irradiation is different from that used in the development of DCFs, this may introduce an error in a calculation. The values in FGR 11 are designed to reflect the probable chemical species expected in the work place; thus, there may be instances in which environmental factors influence the chemical form of the radionuclides and thus the body's retention of the material. Since the dose rate is the important constant, in the case when the clearance time is variable, the calculation of a revised DCF may be appropriate.

E.6.2.3 External Dosimetry

The potential impact of external gamma dose from potential releases from an LLW facility is expected to be minimal. Pathway analysis should indicate the possibility of potential buildup of radionuclides in sediment via water-borne pathways, and can be assessed, if appropriate. Air concentrations from potential releases can be modeled in accordance with acceptable models, as discussed in Section E.5, "Air Transport".

E.6.3 Recommended Approach

The recommended approach is to use pathway DCFs (PDCFs) for calculating doses via the potential exposure pathways. The PDCFs should convert radionuclide concentrations in an environmental locale (i.e. ground water concentration at the well, or air concentration over the crops) to dose equivalent. The PDCF combines both the pathway modeling and the dosimetry modeling in multiplication factors. This approach is described in the DEIS for Part 61. An applicant should document and justify, on a site-specific basis, the use of its PDCFs.

The approach outlined in Figure 15 is a generalization of an acceptable approach to modeling the potential pathways and doses to humans. This approach is consistent with the iterative approach identified in Section C.2 of this technical position. The figure reveals that the many of the considerations concerning pathways and parameter values need to be integrated with other modeling areas for overall consistency of the performance assessment. The approach is explained in greater detail below.

E.6.3.1 Pathway Identification

The applicant should apply a "current conditions" philosophy regarding choice of pathways to be evaluated. Thus, current regional land use and local conditions will strongly influence pathways that are considered to be significant. The applicant should explicitly identify and document the pathways considered in its performance assessment, at an early stage in the performance assessment process. The identification of pathways should be consistent with the types of transport in the conceptual model. Figure 15 shows generalized pathways to consider for releases from a low-level waste facility. Pathway identification is discussed in various literature sources, such as NUREG/CR-5453 Vol.1 (Shipers, 1989).

E.6.3.2 Model Identification and Identification of Parameter Values

Pathway modeling for dose assessment is discussed in a wide array of literature sources (Till

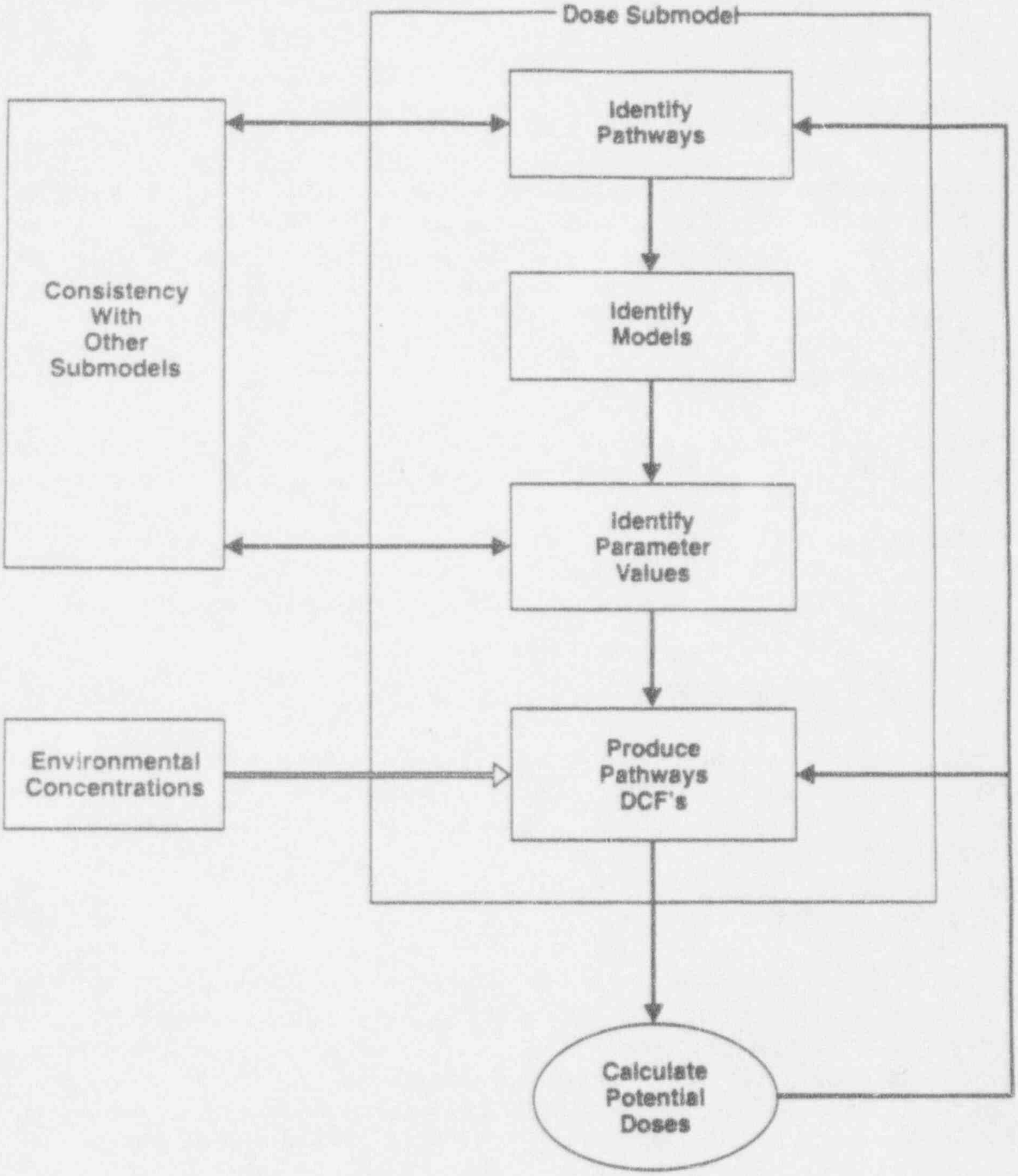


Figure 15. Approach for modeling potential pathways and dose to humans.

and Meyer, 1983). The models suggested for pathway analyses in this technical position, are simple mathematical formulations to reflect transfer compartments in the environment. These formulations are documented in various places and are based on models described in Regulatory Guide 1.109, Rev. 1 (NRC, 1977a), and NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992). The following items should be considered in developing a pathway modeling approach and selection of parameter values.

(1) One acceptable approach for modeling the transport of radionuclides through the biosphere employs transfer factors and bioaccumulation factors. An applicant should document the sources of soil-to-plant, plant-to-animal, and other transfer factors used. Food production and consumption rates should also be documented. Regulatory Guide 1.109 provides conservative values for a variety of these factors. Regional or local parameters or ranges of parameters should be used if this data is available, as discussed below. Generic parameter values found in the literature need to be documented as to their applicability to the expected site conditions and the applicant should attempt to represent a best estimate of the actual values at the site. To attempt to contain the uncertainty in the generic parameter values, a minimum number of sources of information should be used. By using fewer sources, the data should be reasonably internally consistent.

(2) Tritium (^3H) and Carbon-14 (^{14}C) should be carefully evaluated in a performance assessment. Both isotopes appear to be widely distributed in the environment, if released. Thus, specific activity models are generally used to describe their movement through the terrestrial biosphere, and may be acceptable for dose assessment. The parameters used for this model relate the ratio of stable isomer to radioactive isomer in the pathway under evaluation. If data can be found to support the use of this model for alternate isotopes, details of parameters used should be provided by the applicant.

(3) Regional food production and consumption rates are acceptable, and are available through a variety of sources, including US census information and other site-specific studies (e.g., Baes, et al., 1984). Regulatory Guide 1.109 values are acceptable, but appear to be highly conservative, because of their intended use in reactor accident assessments. Regionally specific information should be used, if available.

(4) Bioaccumulation factors in surface water food sources are found in various literature sources, including Regulatory Guide 1.109 and Kennedy and Strenge (1992). If surface water pathways are plausible and can support aquatic foods for human consumption, then this pathway may be significant in a performance assessment. Realistic assumptions regarding available aquatic species and production and consumption rates should be made when considering the surface-water pathway.

The NRC staff recognizes the conservatism in these models; however, in the absence of more sophisticated modeling, which may be justified on a case-by-case basis, this approach is acceptable. If more complex models are used, they should be developed to allow the sensitivities and uncertainties associated with the models, as well as the parameters, to be evaluated. Because of the site-specific nature of performance assessment for LLW facilities, the applicant should obtain the best available data for food generation and consumption rates, irrigation rates and durations, and other values used in dose modeling. NRC staff will not provide default values for use.

An acceptable general approach to resolving unique issues discussed above is a tiered approach, consistent with the iterative approach discussed above. First, simple models and single parameter values are to be used for modeling the potentially complex systems (e.g., Kennedy and Strenge, 1992). If this approach is not sufficient to demonstrate compliance, next, simple models and parameter ranges should be considered, which encompass all realistic parameter values and quantify the uncertainty associated with the parameters. This approach may identify the sensitivity of the model to those parameters.

E.6.3.2 Dosimetry

In this section an acceptable dosimetry methodology is described for calculating doses. Considerations that should be addressed by an applicant include: (1) internal dosimetry methodology and calculation; (2) external dosimetry methodology and calculations; and (3) influence of dose rate on dose assessment. Other considerations that influence model or parameter choice should be documented, as appropriate.

E.6.3.2.1 Internal Dosimetry

The use of DCFs from FGR 11, developed from ICRP 26/30 methodology, which is also the basis for the methodology in Part 20, is recommended. These DCFs are provided in sievert/becquerel or millirem/curie, for intakes identified as either inhalation or ingestion. Assumptions regarding human activity and uptake rates and human organ weighting factors are identified in ICRP 26 and also appear in Part 20.

The NRC staff recommends the use of the DCFs provided in FGR 11. These values were developed for the protection of radiological workers in relatively high-activity situations and are considered a conservative set of values for environmental concentrations and activity levels. The use of conservative dose conversion values may overestimate the dose by 2 or 3 times.

E.6.3.2.2 External Dosimetry

The following approach has been identified as appropriate for external dose calculation, from the potential release of radionuclides, in a performance assessment. Potential doses can be calculated using tabulated dose rate conversion factors (e.g., Kocher, 1981), which predict dose rates from volume sources, and conservatively assume infinite contaminated source conditions for surface contamination conditions or immersion conditions. Shielding from potential over-burden and/or buildings should be considered. NRC staff recommends the use of dose rate conversion factors for evaluating external doses. The use of dose rate conversion factors can be easily incorporated in the development of pathway DCFs, as discussed in the DEIS for Part 61 (NRC, 1981).

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