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Technically Feasible Systems for the Disposal of Greater-Than-Class C Low-Level Radioactive Waste

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ABSTRACT

Development of permanent disposal capacity for greater-than-class C low-level radioactive waste (GTCC LLW) requires the evaluation of potential disposal concepts in terms of technical feasibility, economics, and institutional concerns. Data from previous studies that identified 13 potential GTCC LLW disposal concepts and that characterized the volumes and types of GTCC LLW were used along with newly developed data on concept designs and hypothetical sites to evaluate each concept's performance over 100,000 years.

Performance was evaluated in terms of confinement and intrusion. Specific performance measures for which deterministic and probabilistic calculations were performed are:

- Confinement
  - Total releases
  - Groundwater concentrations
  - Radiation doses
- Intrusion
  - Potential intention events
  - Intrusion consequences.

Order-of-magnitude costs were also developed as a preliminary step in the conduct of a separate economic analysis.

It has been determined that there are two technically feasible disposal systems. The recommended disposal system at an arid site makes use of either the near-surface modular concrete canisters concept, the intermediate depth drilled holes concept, or the intermediate depth mined cavity concept. Order-of-magnitude costs for the recommended arid system range from \$191,000,000 and \$59,000/m^3 to \$293,000,000 and \$90,000/m^3. The recommended disposal system at a humid site makes use of only intermediate-depth or deep geologic disposal concepts; either drilled holes or mined cavities could be used. Order-of-magnitude costs for the recommended humid system range from \$273,000,000 and \$84,000/m^3 to \$396,000,000 and \$122,000/m^3.

SUMMARY

In 10 CFR Part 61, the U.S. Nuclear Regulatory Commission (NRC) developed a classification system for low-level radioactive waste (LLW). The system defined three classes of LLW -- Classes A, B, and C. Waste determined by the NRC to be generally unsuitable for near-surface disposal are commonly referred to as greater-than-class C low-level radioactive waste (GTCC LLW). Although the Low-Level Radioactive Waste Policy Act of 1980 assigned responsibility for the disposal of LLW (including GTCC LLW) to the states, responsibility for GTCC LLW was later transferred to the federal government in the Low-Level Radioactive Waste Policy Amendments Act of 1985.

The responsibility has been assumed by the U.S. Department of Energy (DOE). Long-term management of this waste by DOE is supported by the EG&G Idaho, Inc., GTCC LLW Program. Commercial GTCC LLW must be disposed of in a facility licensed by the NRC. NRC further requires that GTCC LLW be disposed of in a geologic repository, unless DOE proposes an alternative that can be shown to adequately protect the public health, safety, and the environment, and is approved by the NRC.

DOE is investigating alternatives for disposal of GTCC LLW in near-surface, intermediate-depth, and deep geologic facilities. Rogers and Associates Engineering Corporation (RAE) was contracted to perform a technical evaluation of 13 disposal concepts. This report documents the technical evaluation and provides preliminary cost estimates for recommended disposal systems.

RAE developed and applied performance measures, a performance assessment methodology, and characterization data for GTCC LLW categories, disposal concepts and their components, and hypothetical disposal sites. Since regulations have not yet been promulgated for the disposal of GTCC LLW, the performance methodology included a review of the regulatory requirements for low-level and high-level radioactive wastes, which, for the purposes of this evaluation, were considered bounding requirements. From these regulatory requirements, a set of potential required facility requirements and functions was developed. These required functions were further expanded into a set of performance measures that could be calculated using standard performance assessment models. The performance measures were categorized as confinement and intrusion. Confinement performance measures relate to the disposal facility in its undisturbed condition and included three specific measures: total releases, groundwater concentrations, and radiation doses. The intrusion performance measures relate to disturbances, and subsequent impacts, from human intrusion events and included a qualitative assessment of potentially applicable intrusion scenarios and a quantitative assessment of resultant human health effects.

In order to determine the performance of the various disposal concepts, the characteristics of the GTCC LLW to be disposed were identified. Four waste categories were developed based on these characteristics: activated metals, process wastes, contaminated equipment and materials, and sealed sources. Conceptual designs were developed for each of the 13 disposal concepts; five near-surface, four intermediate-depth, and four deep geologic disposal concepts. Specific disposal concepts evaluated were as follows:

Near-surface concepts (all using high-integrity containers)

- Shallow-land disposal
- Belowground vaults
- Earth-mounded vaults
- Aboveground vaults
- Modular concrete canisters

Intermediate-depth concepts

- Drilled holes with high-integrity containers in concrete canisters
- Mined cavities with high-integrity containers in concrete canisters
- Drilled holes with high-level-waste type containers in concrete canisters
- Mined cavities with high-level-waste type containers in concrete canisters

Deep geologic concepts

- Drilled holes with high-integrity containers in concrete canisters
- Mined cavities with high-integrity containers in concrete canisters
- Drilled holes with high-level-waste type containers in concrete canisters
- Mined cavities with high-level-waste type containers in concrete canisters

Hypothetical arid and humid site characteristics were also developed and used in the evaluation.

Performance assessment modeling was initially conducted on individual disposal concept components to determine radionuclide release rates from the four waste categories and the multiple barriers incorporated in each disposal concept. These results were then transferred to a systems performance assessment model which was then used to calculate characteristic and probabilistic results for each performance measure.

The results were evaluated to determine the performance of each concept in relation to the performance of the other disposal concepts. Performance measures were calculated for each waste category and a composite category where all GTCC LLW is disposed of in the same concept. The performance results were evaluated, giving the greatest weight to the confinement radiation dose measure and the intrusion health effects measure. Based on the evaluation two disposal systems are recommended as being technically feasible. The arid site disposal system makes use of either the near-surface modular concrete canisters concept, the intermediate-depth drilled holes concept, or the intermediate-depth mined cavity concept. The humid site disposal system makes use of only intermediate-depth or deep geologic disposal concepts. Either drilled holes or mined cavities would be used.

The order-of-magnitude costs for the recommended arid site system range from \$191,000,000 to \$293,000,000 for a per-cubic-meter cost of \$59,000/m^3 to \$90,000/m^3. The order-of-magnitude costs for the recommended humid site system range from \$273,000,000 to \$396,000,000 for a per-cubic-meter cost of \$84,000/m^3 to \$122,000/m^3.

CONTENTS

FIGURES

TABLES

ACRONYMS

ACI	American Concrete Institute
ASTM	American Society of Testing and Material
CFR	Code of Federal Regulations
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
ERM	Environmental Resources Management - Program Management Company
GTCC	greater-than-class C
LLW	low-level radioactive waste
NRC	U.S. Nuclear Regulatory Commission
PL	public law
RAE	Rogers & Associates Engineering Corporation
TRU	transuranic
UBC	Uniform Building Code

Technically Feasible Disposal Systems for the Disposal of Greater-Than-Class C Low-Level Radioactive Waste

1. INTRODUCTION

As part of its Greater-Than-Class C Low-Level Waste Project, EG&G Idaho, Inc., contracted with Rogers & Associates Engineering Corporation (RAE) and ERM Program Management Company (ERM) to develop a technical evaluation report recommending feasible combinations of technologies for the disposal of greater-than-class C (GTCC) low-level radioactive waste (LLW). The recommended disposal technologies are based on long-term performance. Specifically, the ability of the technologies to contain, or isolate, GTCC LLW within the area of the disposal unit (the disposal horizon) and minimize the possibility and consequence of inadvertent human intrusion.

Previous studies (DOE 1991a, DOE 1991b) developed lists of potential disposal technologies for evaluation. Those technologies span the range from near-surface through intermediate-depth to deep geologic conditions. The technologies included disposal configurations ranging from shallow land disposal to the use of canisters and vaults for near-surface disposal to various combinations of containers and barriers in mined cavities and drilled holes. Thirteen specific disposal concepts, making use of four distinct technical components, were identified and recommended for further technical evaluation. They included five near-surface concepts, four intermediate-depth concepts, and four deep geologic concepts.

This study presents a set of technical evaluation criteria, describes conceptual designs for the 13 potential GTCC LLW disposal concepts, characterizes hypothetical sites, details the characteristics of the GTCC LLW inventory, and reports the results of comparative performance assessments of each potential disposal concept. Using the conceptual designs and standard cost-estimating procedures, preliminary cost estimates were prepared and are presented in this report.

1.1 Background

In 10 CFR Part 61 (NRC 1982), the U.S. Nuclear Regulatory Commission (NRC) developed a waste classification system defining three classes of LLW -- Classes A, B, and C. Waste determined by the NRC to be generally unsuited for near-surface disposal without additional protection (typically intruder protection) is commonly referred to as GTCC LLW. The Low-Level Radioactive Waste Policy Act of 1980, Public Law (PL) 96-573, assigned the responsibility for disposal of LLW, including GTCC LLW, to the states. Under NRC regulations, any disposal of GTCC LLW was to be approved on a case-by-case basis.

The Low-Level Radioactive Waste Policy Amendments Act of 1985 (PL99-240) transferred the responsibility for disposal of commercially generated GTCC LLW from the states to the federal government. This responsibility has been assumed by the U.S. Department of Energy (DOE). The EG&G Idaho GTCC LLW Program supports DOE in the long-term management of this waste.

Commercial GTCC LLW must be disposed of in a facility licensed by the NRC. The NRC has promulgated regulations (NRC 1989) requiring GTCC LLW to be disposed of in a geologic repository [as defined in 10 CFR 60 (NRC 1982), the NRC regulations governing disposal of high-level radioactive waste], unless DOE proposes an alternative disposal technology that can be shown to adequately protect public health and safety and the environment and is approved by the NRC.

Present waste management strategy for GTCC LLW includes providing limited near-term interim storage (for case-by-case health and safety concerns) and dedicated storage of commercial GTCC LLW until disposal capacity is available. Figure 1-1 is a summary of the DOE's three-part GTCC LLW management strategy.

DOE is investigating alternatives for disposal of GTCC LLW in near-surface, intermediate-depth, and deep geologic disposal facilities. In order to evaluate and select the most preferred disposal concepts for further development, the following three evaluations are performed in series: technical, economic, and institutional. Each of these evaluations serves as a screen, allowing only those disposal concepts that are deemed feasible to pass through for further evaluation.

Screening of possible disposal technologies was completed in 1991 (DOE 1991a, DOE 1991b). The objective of this report is to present an evaluation of the technical feasibility of the 13 specific disposal concepts identified in that screening. Each disposal concept is made up of a disposal technology employed at a specific disposal depth, either near-surface, intermediate-depth, or deep geologic.

If DOE proposes a disposal facility other than a geological repository for GTCC LLW, the requirements the NRC will use to license the facility are not presently known. It is assumed, however,

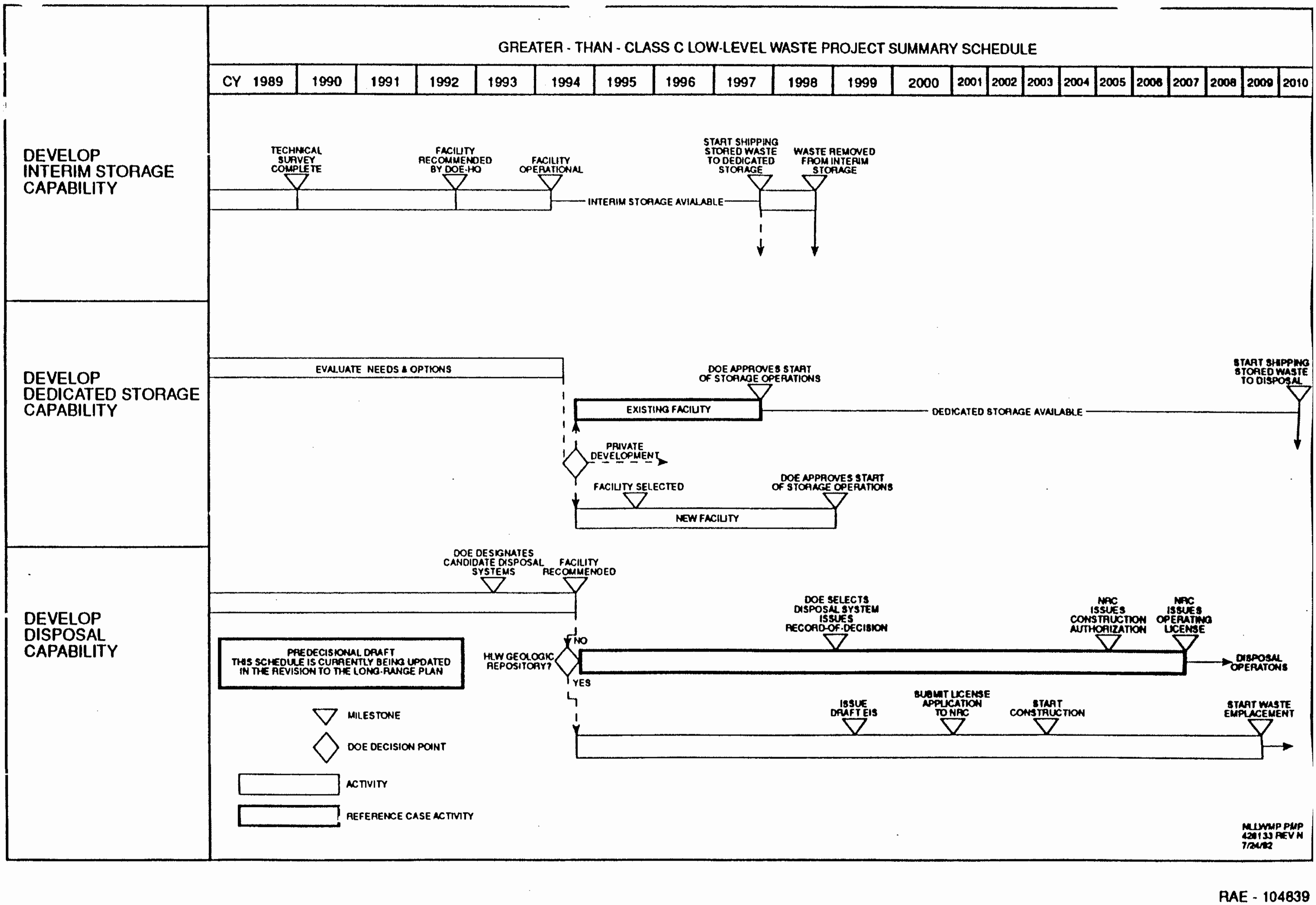


Figure 1-1. DOE strategy for managing GTCC LLW.

that the licensing requirements will be bounded by those in existing regulations for LLW (10 CFR Part 61) and high-level waste, 10 CFR Part 60 (NRC 1986). The specific licensing requirements will depend on the disposal concept proposed by DOE.

1.2 Purpose

The long-term strategy for the development of disposal capability for GTCC LLW (Figure 1-1) is to provide a licensed facility or facilities for final disposal. Previous studies (DOE 1991a, DOE 1991b) of near surface, intermediate depth, and deep geological disposal concepts identified several concepts for technical, economic, and institutional evaluation. The objectives of this report are to (1) describe and report the results of the technical evaluation of the identified GTCC LLW near surface, intermediate depth, and deep geologic disposal concepts, (2) present order-of-magnitude cost estimates, and (3) recommend technically feasible disposal systems.

1.3 Report Organization

This report is organized into eight sections. Section 1 includes an introduction and background to GTCC LLW and the DOE program assigned to manage it. The purpose of this report and its place in the DOE GTCC LLW management strategy is described.

Section 2 summarizes the previous studies of potential disposal concepts for GTCC LLW. It also outlines the various activities involved in the further evaluation of the remaining concepts to allow selection of recommended disposal systems. Section 3 describes the derivation of the performance measures used in the technical evaluation and provides a description of the technical evaluation methodology. The characteristics of GTCC LLW, the disposal concept, and the disposal sites that are important to the technical evaluation are presented in Section 4. Section 5 presents the results of the technical evaluation and discusses the sensitivity of these results to the data, assumptions, and evaluation methods used. Section 6 discusses the identification of technically feasible disposal systems. The order-of-magnitude cost estimates for the various disposal concepts undergoing the technical analysis and for the technically feasible disposal systems are presented in Section 7. Report conclusions are presented in Section 8.

2. DEVELOPMENT OF GTCC LLW DISPOSAL CAPABILITY

The DOE has developed the overall scope and sequence of activities necessary to select the disposal system for GTCC LLW (DOE 1992a). As shown in Figure 2-1, the activities contained in blocks 1 through 3 will be completed to decide if all GTCC LLW will be disposed of in the high-level waste repository or at an alternative facility. Should an alternative disposal facility be selected for either all or a portion of GTCC LLW, the activities shown in blocks 4 through 13 of Figure 2-1 will be conducted.

As stated in Section 1, the objectives of this study are to (1) describe and report the technical evaluations of the identified GTCC LLW near-surface, intermediate-depth, and deep geologic disposal concepts, (2) develop and present order-of-magnitude cost estimates for each concept, and (3) recommend technically feasible disposal systems. These three objectives are achieved by conducting the work in blocks 1b and 1c of Figure 2-1. The following sections place the technical and economic evaluations in context of previous work (block 1a) and of subsequent disposal concept development activities.

2.1 Designate Disposal Concepts

The overall logic diagram to be used in designating candidate disposal systems is shown in Figure 2-2. The full range of potential disposal concepts, shown in Figure 2-3, was examined to identify those concepts for screening. More focused evaluations were then made of the potential land-based disposal concepts that could be located in near-surface, intermediate-depth, or deep geologic disposal horizons. The report, Technical Evaluation of Near Surface Disposal Systems for Greater-Than-Class C Low-Level Radioactive Waste, [DOE/LLW-104b (DOE 1991b)], examines potential near-surface disposal concepts. Intermediate-depth and deep geologic disposal concepts are examined in Identification of Potential Intermediate Depth and Deep Geologic Disposal Concepts for Greater-Than-Class C Low-Level Radioactive Waste, [DOE/LLW-104a (DOE 1991a)].

Both reports, starting with the full range of potential disposal concepts (Figure 2-3), applied a sequential screening to arrive at a subset of disposal concepts which were then evaluated. The sequential screening processes both use economic, regulatory, environmental, technical, and institutional factors, while differing to some degree on the specific criteria and the screening techniques used. The screening approach for each study employed a group of selected individuals to apply subjective judgements to rank the concepts in terms of each factor.

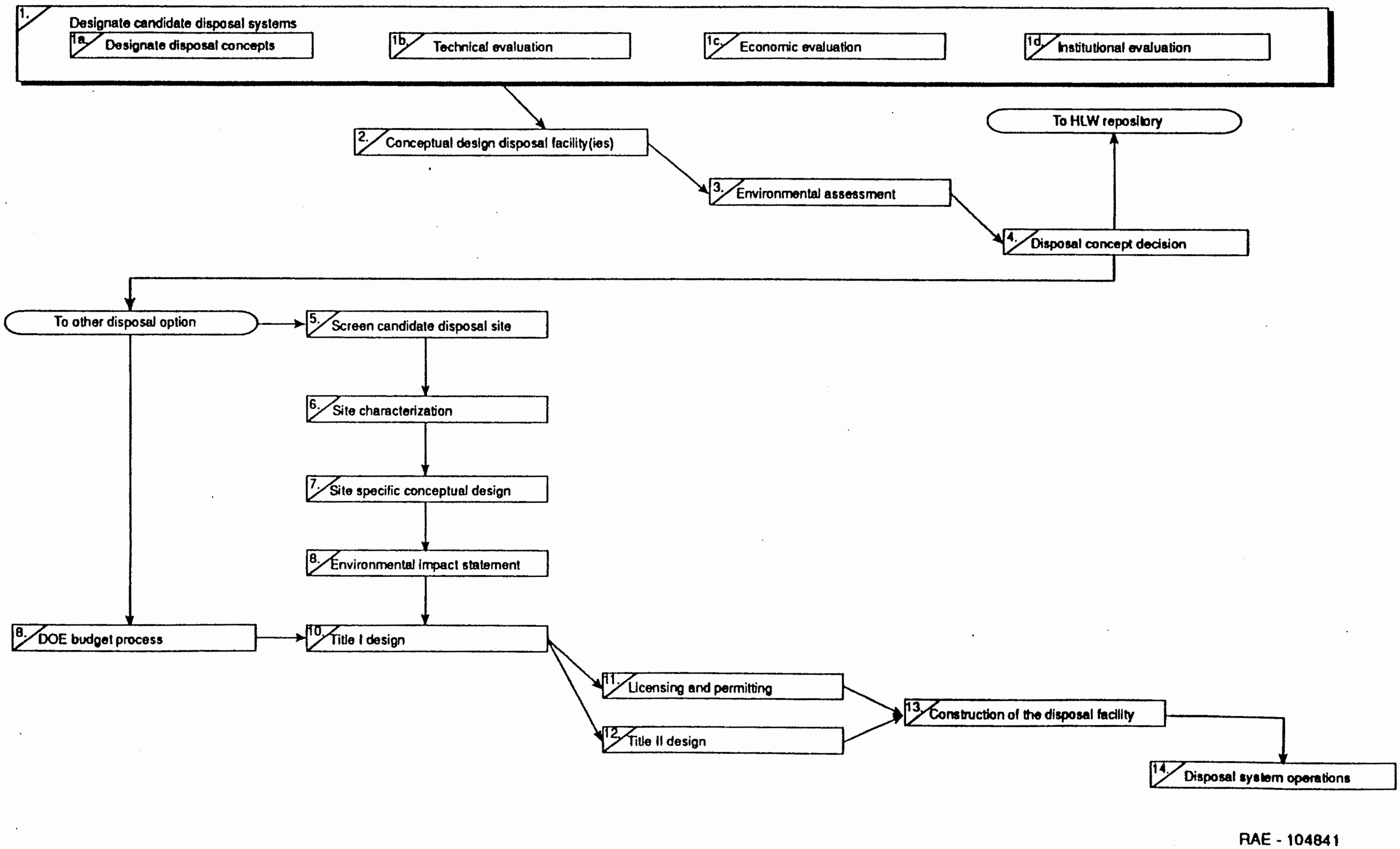


Figure 2-1. GTCC LLW disposal facility development logic diagram.

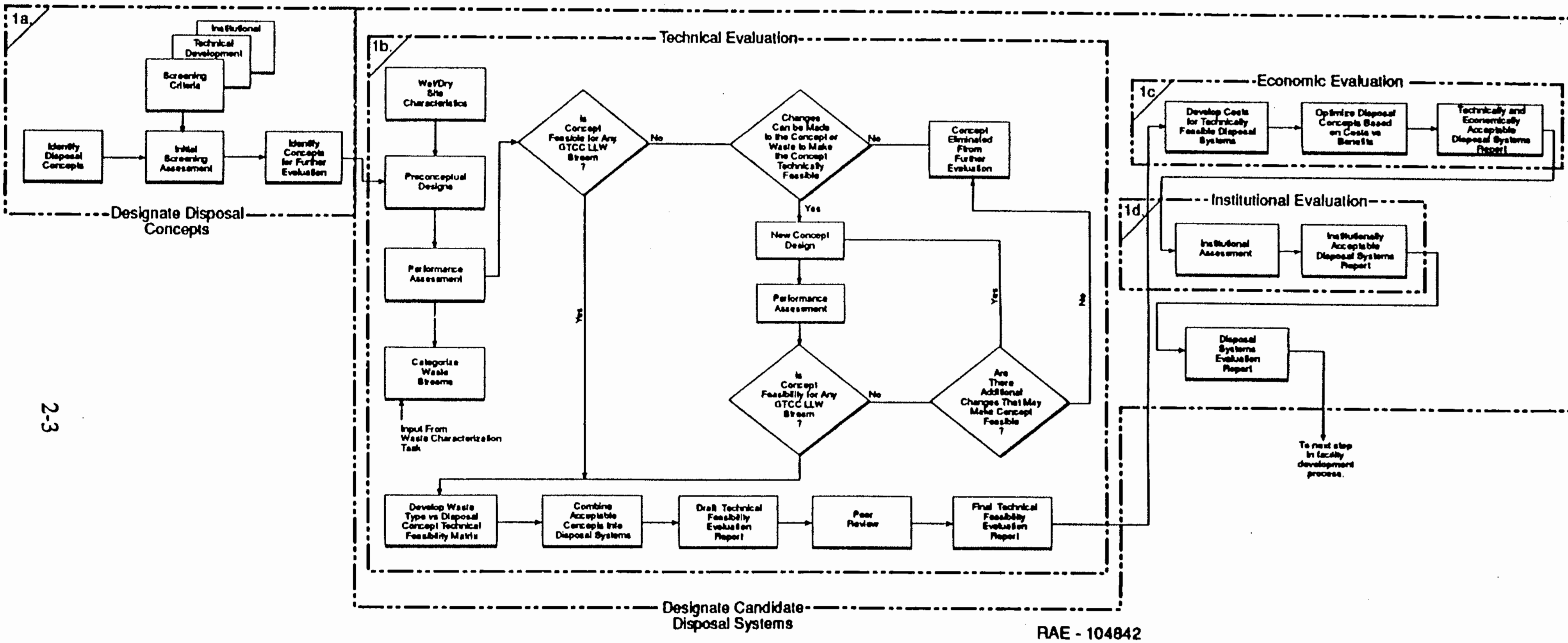


Figure 2-2. Designate candidate disposal systems activities.

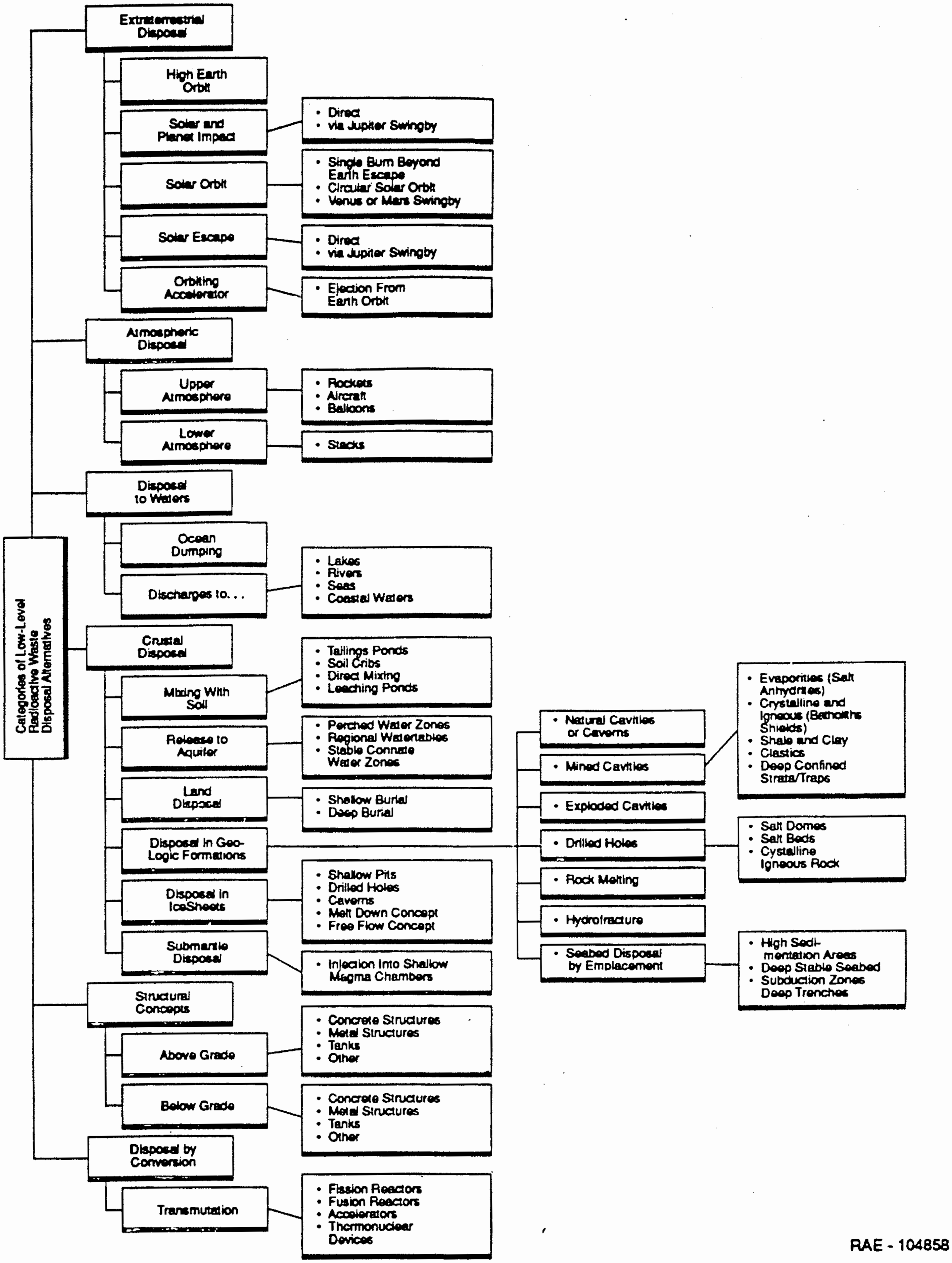


Figure 2-3. Comprehensive listing of LLW disposal concepts (adapted from Ref.6).

In the study of near-surface concepts, nine generally defined disposal concepts were identified for screening. These nine concepts were considered usable in the upper 30 meters of the earth's surface. Based on results of the initial screening, shallow land disposal and four alternative concepts were judged suitable for further detailed evaluation. Those five concepts are:

- Shallow land disposal
- Belowground vault
- Modular concrete canisters
- Aboveground vault
- Earth-mounded concrete vault.

The five near-surface concepts identified did not define the type of waste package or placement configurations to be used. Defining these elements of the near-surface disposal concepts is necessary in order to evaluate technical feasibility and economics. The concepts as identified in DOE 1991b, were therefore modified to include definitions for the type of waste package and package placement configurations.

The study of intermediate-depth and deep geologic disposal options started with the same list of total potential disposal options (Figure 2-3) as used in the study of near-surface disposal concepts. The focus, however, was on the disposal concepts considered viable at depths greater than 30 meters. Unlike the near-surface study, the potential disposal concepts examined in the intermediate-depth study were defined in terms of potential components. These components included construction configuration, engineered barriers, waste packages, and waste placement methods. Table 2-1 is a listing of the range of disposal concept components considered.

Combining all possible combinations of components identified a total of 116 disposal combinations for screening. As a result of the screening, eight disposal concepts were identified for further evaluation. These eight concepts, defined in terms of disposal horizon, construction method, placement method, waste package, and barrier used are:

Table 2-1. Range of intermediate depth and deep geologic disposal concept components considered.

<u>**Construction Configurations**</u>
Mined cavity
Drilled hole
Man-made void
Open excavation
<u>**Barriers**</u>
Vault
Canister
Backfill
<u>**Waste Packages**</u>
LLW-type container
High-integrity container
High-level waste type container
<u>**Emplacement Configurations**</u>
Layered placement
Borehole placement

- Intermediate depth
  - Mined cavity - layered placement - high-level-waste type container - canister
  - Mined cavity - layered placement - high-integrity - canister
  - Drilled hole - layered placement - high-level-waste type container - canister
  - Drilled hole - layered placement - high-integrity - canister

- Deep geologic
  - Mined cavity - layered placement - high-level-waste type container - canister
  - Mined cavity - layered placement - high-integrity - canister
  - Drilled hole - layered placement - high-level-waste type container - canister
  - Drilled hole - layered placement - high-integrity - canister

2.2 Evaluations of the Designated Disposal Concepts

Figure 2-2 shows that the disposal concepts identified undergo, in series, technical (block 1b), economic (block 1c), and institutional (block 1d) evaluations. Completion of those three evaluations results in the selection of disposal systems for conceptual design and environmental assessments (blocks 2 and 3 of Figure 2-1). Because these are the first evaluations conducted for each disposal concept, it is important to ensure that enough detail is developed so that the technical evaluation supports the economic and institutional evaluations. Redefining the concepts for subsequent evaluations could result in designs with sufficiently different characteristics to make consistent comparison impossible. The scope and objectives of the economic and institutional evaluations must, therefore, be kept in mind in order for the disposal concepts (as characterized for the technical evaluations) to be sufficient for all three.

2.2.1 Technical Evaluation

This study is to determine which of the identified disposal concepts are technically feasible and can therefore be considered for inclusion in a GTCC LLW disposal system. Technically feasible concepts are concepts that have been analyzed for performance under generalized site conditions and have been found to have characteristics and performance measures that indicate that regulatory requirements can be met over a broad range of site conditions. The analysis uses performance assessment techniques developed for this project using accepted approaches, as presented in DOE 1988a and DOE 1992b, and existing computer codes. A humid and an arid site were defined in order to represent a range of physical site conditions. Conceptual designs were developed for each of the disposal concepts using, to the extent possible, standardized components to aid comparison and subsequent analyses. GTCC LLW inventory and characteristics were summarized from DOE 1991c and DOE 1992c, and release mechanisms defined for each of the four categories of waste were defined. Finally, performance measures were defined to represent the regulatory performance requirements for confinement and for preventing human intrusion into the waste. These measures were designed to represent the requirements for both high-level waste disposal and LLW disposal, in order to present bounding criteria to use in comparing the various disposal concepts. The methodology and the techniques used to implement it provide one-to-one correlations between the selected performance measures and the results produced by the methodology.

The performance assessment methodology is designed to provide relative and not absolute measures of disposal concept performance. It is applicable to all the designated disposal concepts and equally applicable across the range of arid and humid site characteristics. Arid and humid site characteristics are developed and configured to represent a range of possible disposal sites. Differences in the site characteristics are selected so as to highlight the performance of the various disposal concepts and not to cause the concept's performance to be masked by poor site performance characteristics. Each designated disposal concept is designed to the extent that the contribution provided by the concept's various components to the concept's overall containment and isolation performance can be estimated. To ensure consistency, a common set of design basis requirements is used for development of these conceptual designs.

Technical evaluation in Figure 2-2 involves a sequence of design and evaluation steps. These steps are repeated until a design either can be used to dispose of at least a portion of GTCC LLW or can not be further enhanced. The same result is achieved using a well defined initial conceptual design which includes the range to which a concept can be improved. Developing such conceptual designs requires a thorough understanding of the characteristics and features of the concept and how they affect its performance. The behavior of the initial conceptual design's characteristics are modeled using computer codes simulating the interactions between its technical components, the waste it contains, and the physical disposal environment. Characteristics of the disposal concept having a major impact on its performance is defined as both a range and base case or design value. Probabilistic and deterministic calculations are made to determine the performance based on the design values and the range of performance that may be achieved if different design values from within the range were selected.

The designated concepts were defined to support the economic evaluation by developing order-of-magnitude costs for each concept. This ensured that each concept would provide a basis for assigning an estimated cost. The development of detailed costs are part of the subsequent economic evaluation.

Each disposal concept undergoing technical evaluation was characterized to support an institutional analysis. The institutional factors associated with alternative near surface, intermediate depth, and deep geological disposal concepts for GTCC LLW were examined as part of selecting the designated disposal concepts (DOE 1991a, DOE 1991b). Further characterization of the disposal concepts in terms of those factors was unnecessary and therefore not conducted as part of the technical evaluation.

2.2.2 Economic Evaluation

A set of standard financial analyses is conducted for each recommended disposal system. The objective of each analysis is to provide information sufficient to agree on, compare, and arrive at the most cost-effective and economic characteristics of the different disposal systems. Standard accepted constant-dollar, present-value, and current-dollar estimates are used. Those estimates, the relative importance of each estimate to the other, and the technical performance of the system form the basis for arriving at the most cost-effective and economical system.

2.2.3 Institutional Evaluation

The institutional evaluation incorporates the technical and economic evaluations and serves as the starting point to assess regulatory, social, and other nontechnical and economic issues related to developing the recommended disposal systems. The institutional evaluation will identify potential social and institutional problems related to the disposal of GTCC LLW and provide recommendations to solve them. This information will be used in the overall siting, licensing, construction, operation, and closure processes.

3. TECHNICAL EVALUATION METHODOLOGY

The technical evaluation to identify and recommend feasible disposal systems is divided into three components. These are (a) the development of performance measures based on regulatory requirements, (b) the actual assessment of disposal system performance with computer codes, and (c) a sensitivity analysis to examine combined and individual concept and component sensitivities. The purpose of this chapter is to describe the methodology used to develop each of these components and how they will be combined with the disposal concepts and site characteristics presented in Section 4 and used in the performance assessment process to yield the results presented in Section 5.

3.1 Overall Methodology

The overall methodology examines regulatory requirements to develop a set of performance measures for comparison of various disposal concepts. Since no specific regulatory requirements have been promulgated for GTCC LLW, it is assumed that any requirements that may be developed will be bounded by the requirements for LLW and high-level waste. Those regulatory requirements are used to develop the performance measures in this study.

Developing performance measures is followed by selecting a calculational methodology to implement them. This was accomplished by breaking down the performance assessment of the disposal concepts into common components. Simple calculations and/or models were used to analyze components of the disposal systems such as release rates and barrier performance (containers, canisters, and vaults).

The results of the calculations were used as input to a systems performance assessment model that allows the use of distributed data. This model pulls all of the components together and addresses each of the pertinent performance measures.

3.2 Performance Measures

The NRC has declared that GTCC LLW must be disposed of in a licensed geologic repository or in a facility specifically approved by the NRC. In those instances where a repository would not be used, it is the NRC's position that the containment requirements for the GTCC LLW would be the same as those for the high-level waste repository, unless lesser requirements were found to be sufficient. Of the requirements contained in 10 CFR 60 (NRC 1983), some apply to the waste, others apply to the disposal site, and still others to the facility. Questions, therefore, remain about the regulatory requirements that might be applied to the disposal of GTCC LLW at intermediate depth, in deep geologic settings, or in repository-related facilities.

Since regulations specific to the disposal of GTCC LLW are yet to be developed and issued, the existing regulations for LLW (10 CFR 61) and high-level waste (10 CFR 60) are referred to in this document for guidance as to what those regulations may require. Both of these sets of regulations declare siting, design, and other criteria that can be useful in determining a set of regulatory requirements that might reasonably be applied to the disposal of GTCC LLW. The regulatory requirements can in turn be related to required functions that any GTCC LLW disposal option must perform.

The functions that each GTCC LLW disposal concept must perform are fundamental to the successful performance of the disposal system and are referred to as "required functions." The required functions for all of the disposal technologies or to which the technologies must contribute, whether applicable to LLW or high-level waste disposal, are summarized below:

- Protect the general population from releases of radioactivity (10 CFR 61.41 and 10 CFR 60.113)
- Protect individuals from inadvertent intrusion (10 CFR 61.42)
- Protect individuals during operations (10 CFR 61.43 and 10 CFR 60.111)
- Ensure stability of the disposal site after closure (10 CFR 61.44 and 10 CFR 60.133)
- Minimize waste coming in contact with standing water (10 CFR 61.51, 10 CFR 60.133, and 10 CFR 60.134)
- Stabilize waste form (10 CFR 61.56 and 10 CFR 60.135)
- Ensure structurally stable waste packages (10 CFR 61.56 and 10 CFR 60.113)
- Maintain retrievability option (10 CFR 60.111).

Based on the required functions listed above, two categories of performance measures were developed. These are: (a) measures for undisturbed conditions (referred to as confinement) and (b) measures for disturbed conditions (referred to as intrusion). The performance measures within each of the two categories are discussed in the following sections.

Performance Measures for Confinement

The three performance measures selected for the confinement category are (a) cumulative radionuclide release, (b) time-dependent groundwater concentrations, and (c) relative impact on an individual. The location where each disposal concept is assessed in terms of each performance measure is shown in Figure 3-1.

Cumulative Radionuclide Release. Cumulative releases will be evaluated for each radionuclide and the total waste inventory at the base of each disposal concept (locations marked A in Figure 3-1). This performance measure accounts for the ability of each disposal concept to isolate radioactive material from the environment, and is a direct measure of the performance of the engineered barriers (canister, vault, or waste container) and the waste form. The cumulative release will be determined by the amount of water percolating through the disposal site and the collective performance of the engineered features employed in each disposal concept. The engineered features for the various concepts are shown in Table 3-1.

The magnitude of a release and its timing depends on the sequence and timing in which the various barriers fail and the rate at which radionuclides are released from the various waste matrices. Taken together, the sequence of failures and then the release rate can be displayed graphically as a time-dependent release profile, as shown in Figure 3-2.

Time-Dependent Groundwater Concentrations. The second performance measure for the confinement category is the time-dependent radionuclide concentrations in groundwater at a monitoring well located one meter from the edge of the disposal facility (location B in Figure 3-1). This measure of performance is designed to account for the added effects of transit time and dilution as the released radionuclides migrate vertically from the base of the facility to the aquifer, and horizontally to the monitoring well.

The performance represented by the concentration of radionuclides in groundwater will differ from the cumulative radionuclide release because of the vertical transit time necessary for radionuclides to travel from the disposal horizon to the aquifer. For the arid site, this will be the time necessary to reach the aquifer below the deep geologic disposal horizon as shown in Figure 3-1. For the humid site, the aquifer may be different for each disposal horizon. The location and number of humid site aquifers and, therefore, transit distances for each disposal concept will be established by the specific site characteristics.

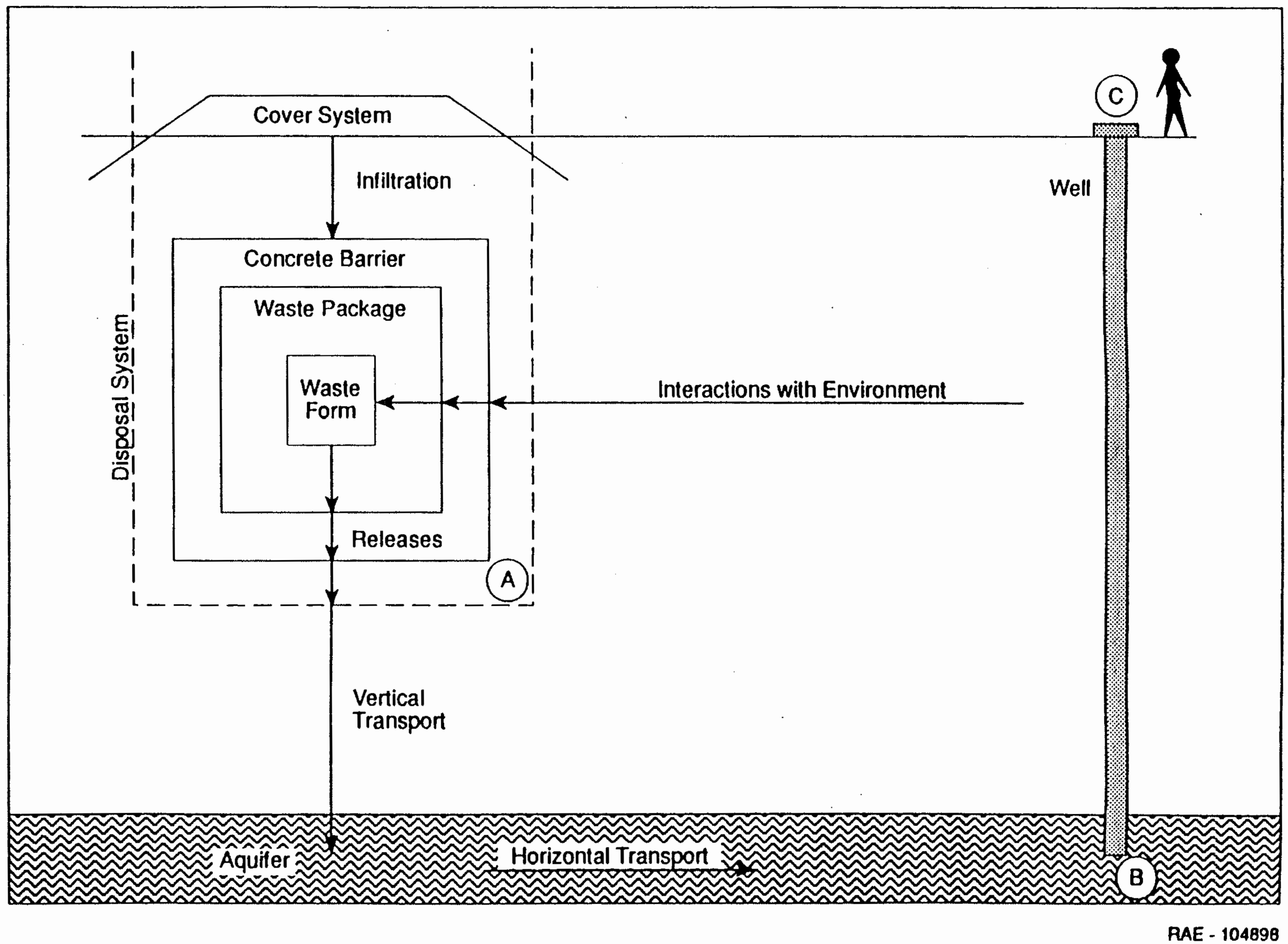


Figure 3-1. GTCC LLW disposal system conceptual model.

Table 3-1. Engineered features for the various disposal concepts.

	Engineered cover	Disposal vault	Modular concrete canister	High-integrity container	High-level-waste type container	Waste form
Shallow land burial	x.					x
Aboveground vault		x				x
Earth-mounded vault	x	x				x
Belowground vault	x	x				x
Modular concrete canisters	x		x			x
Drilled hole/high-integrity container intermediate depth	x		x	x		x
Mined cavity/high integrity container intermediate depth	x		x	x		x
Drilled hole/high-level waste type container intermediate depth	x		x		x	x
Mined cavity/high-level waste type container intermediate depth	x		x		x	x
Drilled hole/high-integrity container deep geologic	x		x	x		x
Mined cavity/high-integrity container deep geologic	x		x	x		x
Drilled hole/high-level waste type container deep geologic	x		x		x	x
Mined cavity/high-level-waste type container deep geologic	x		x		x	x

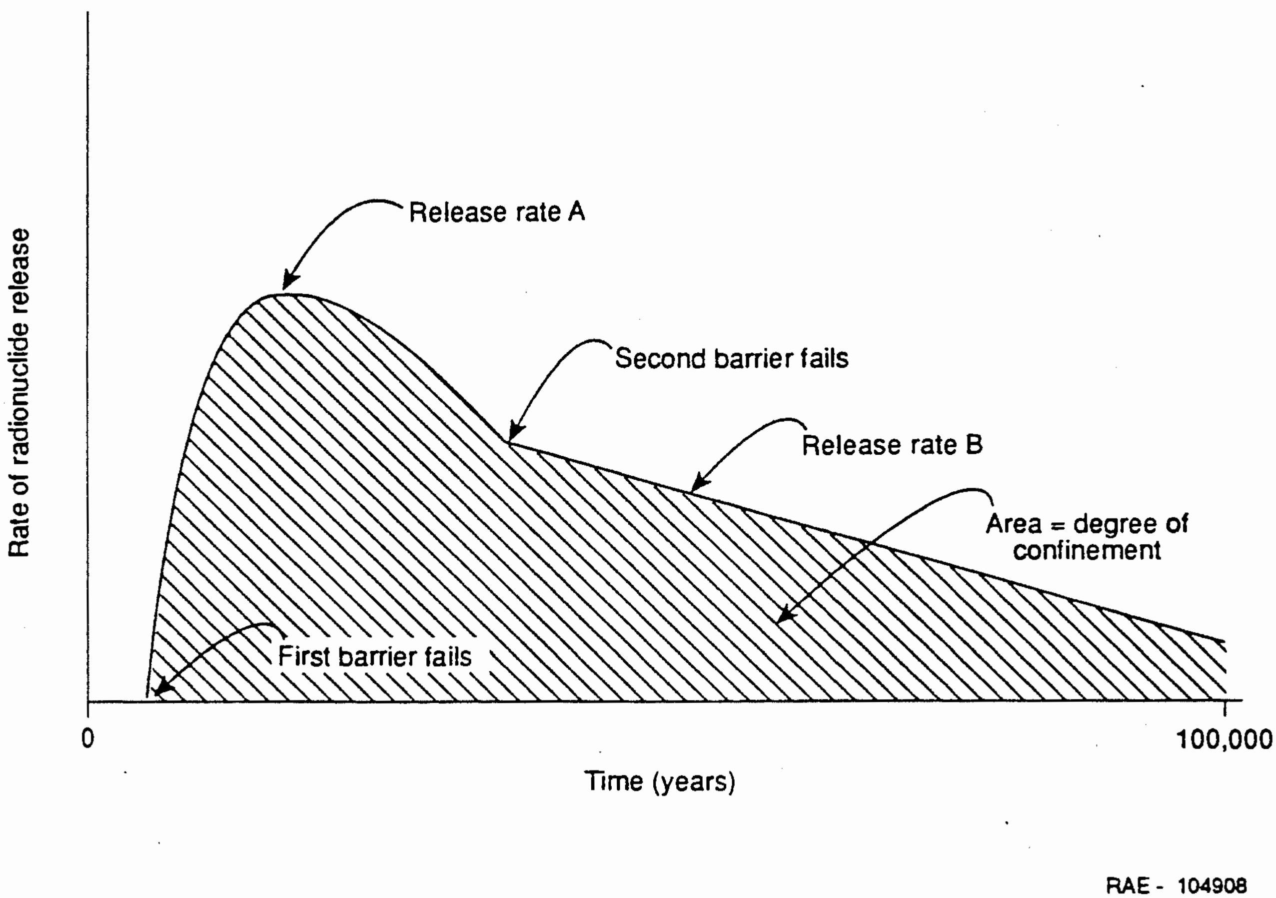


Figure 3-2. Example time versus release profile.

Relative Impact on an Individual. The third performance measure is the potential impact on an individual following the loss of confinement and transport through the environment to a point where a human might have access to the released radionuclides. This impact will be evaluated for an individual consuming two liters a day (consistent with drinking water standards) of groundwater from the 1 m well specified in Figure 3-1 (location C).

The impact on the individual produced by one concept will be compared to the impact from the other disposal concepts. It will not be expressed as a dose, health effect, or other measure that could be compared to regulatory standards.

Performance Measures for Intrusion

The two performance measures selected for the intrusion category are a qualitative evaluation of human intrusion events and the relative impacts of such events. Each of these performance measures is discussed in the following paragraphs.

Qualitative Evaluation of Human Intrusion Events. The first performance measure for the intrusion category is a qualitative evaluation of the types of human intrusion events that may occur for each disposal concept, including: drilling, digging during exploratory activities, and excavating during house construction. Engineered barriers will also influence the occurrence of intrusion events.

The probability that drilling through the waste will occur is considered differently by the NRC and the U.S. Environmental Protection Agency (EPA). In developing 10 CFR 61 (NRC 1982), the NRC assumed that standard drill bits would not penetrate reinforced concrete. Furthermore, they assumed that the driller would move to another location if the bit contacted metal. Based on this approach, a driller-intruder scenario would not be possible until enough time had passed to allow for degradation of all of the engineered barriers. For waste forms composed of metal components, this also would require that the waste be entirely corroded.

In developing standards for the disposal of high-level waste, the EPA assumed that a drill would be able to penetrate rock and metal. Based on this approach, drilling at the site would contact the waste following loss of institutional control.

The presence of three meters or more of cover material over the top of each disposal concept will prevent a standard basement excavation from contacting the top of the disposal facility. If, at some time in the future, fewer than three meters of cover material exist as a result of erosion or some other site-dependent process, the presence of vaults, concrete canisters, waste containers, and recognizable waste will cause the basement excavator or the explorer to dig somewhere else. In order for these types of intrusion to occur, enough time must pass to ensure degradation of the waste form and all engineered barriers.

A second aspect of the qualitative evaluation is the likelihood that an intrusion occurring at the disposal site would contact the waste. Disposal density and total disposal site area will be the major determining factors. Technologies with lower disposal densities per unit surface area of the disposal site are expected to have higher hit-to-miss ratios than technologies with higher disposal densities.

Relative Impact from Each Intrusion Event. The second performance measure for the intrusion category, based on a qualitative evaluation, consists of the relative impacts caused by the intrusion event. If the qualitative evaluation does not identify any applicable intrusion events, then the relative impact is zero and is identical for all disposal concepts. However, it is more likely that, at least for the nonmetallic waste forms, intrusion as a result of drilling will be possible for at least some of the disposal concepts. In the event the depth of the cover over the waste is reduced to fewer than three meters, intrusion resulting from construction may also need to be evaluated.

For each intrusion event requiring analysis, the methodology used in the NRC's Environmental Impact Statement (NRC 1982b) for 10 CFR 61 will be followed. Exposures to the contractor drilling a domestic water well are assessed. In this scenario, waste is brought to the surface by compressed air or with soil and is contained in a mud pit used by the drillers. The drilling contractor is exposed to direct radiation from the water/soil/waste mixture in the pit. The exposure will be influenced by the size of the mud pit, the amount of radioactive material brought to the surface, and the amount of uncontaminated material brought to the surface.

In the construction scenario, impact to the individual is based on the excavation of a basement for a house. During excavation the person may, depending on the depth of the material over the waste, contact the uppermost layer of the emplaced waste. If waste is contacted, exposure may result from inhaling of contaminated dust and from direct exposure.

The interrelationships of environmental conditions at the disposal site. The characteristics of the disposed waste, and the features of the various disposal technologies are varied and complex. The nature of these interactions ultimately determines the effectiveness of the GTCC LLW disposal strategy. Those interactions are shown schematically in Figure 3-1 and are discussed in the following paragraphs.

Site environmental conditions will interact with several aspects of the disposal technology, thereby influencing the effectiveness of the disposal strategy. The engineered cover system may influence the amount of precipitation that eventually contacts the waste. The frequency and duration of site precipitation, in conjunction with other meteorological conditions, may also influence the rate at which the cover system deteriorates, thereby becoming less effective in excluding water from the waste.

The chemistry of water percolating through the cover system downward through the disposal horizon will have a significant impact on the rate at which concrete canisters or vaults, waste containers, and waste forms deteriorate. Rates of degradation of these components will dictate the rates at which waste radionuclides are released to the environment. The point at which contaminants are released outside the disposal system is the point at which the cumulative radionuclide release performance is measured. This is indicated by point A on Figure 3-1.

Radionuclides released from the disposal facility may be transported downward vertically to an aquifer in proportion to the velocity of groundwater in the unsaturated zone at the disposal site. Geochemical characteristics of the transport route will influence the rate at which radionuclides are adsorbed to geologic materials and, hence, the transport velocities of these contaminants. Once radionuclides are discharged to the aquifer, the velocity and chemical characteristics of the groundwater will determine the time required for the contamination to reach a point (i.e., well) that is accessible by humans. This is the point at which the time-dependant groundwater concentration performance measure is measured. This is indicated by point B on Figure 3-1.

From this point, which is conceptually envisioned as the bottom of a well, contaminants are drawn up the well (no dilution is assumed) to a point for human use and subsequent exposure. It is at this point that the relative impact on individuals (dose) performance is measured. This point is indicated by point C on Figure 3-1.

3.3 Component Analysis

The performance of each component of a disposal technology is analyzed separately to determine the specific characteristics it contributes to the performance of the total technology. All of the 13 disposal concepts analyzed contain several components contributing to the performance of the technology, e.g. waste packages, concrete barriers (e.g., canisters or vaults). The specific components for each concept are listed in Table 3-1.

3.3.1 Waste Package Characteristics and Degradation

Disposal packages are the containers in which the waste is placed for disposal. The previous study of near-surface disposal concepts (DOE 1991b) did not identify the type of disposal package used in these technologies. The study on intermediate-depth and deep geologic disposal technologies (DOE 1991a) specified two types of disposal packages; the high-integrity container and the high-level-waste type container. Examples of the former include several high-integrity containers approved by the NRC for the disposal of Class B and C LLW and would include any additional waste packages approved for disposal of this waste in the future. The high-level-waste type container is any container that meets the specific high-level-waste, container design criteria in 10 CFR 60 (NRC 1982a). These criteria address the need to inhibit releases of radionuclides for thousands of years. It is important to note that, while used as a possible container in this evaluation, waste containers meeting the design criteria of 10 CFR 60 are not required to be used in disposing of GTCC LLW.

In all of the disposal concepts other than shallow-land disposal, the waste packages are placed within a second barrier, either a concrete vault or a modular concrete canister. The size and shape of the waste package, the inner dimensions of the canister and the vaults, and the operational weight and radiation restrictions on the canister determine the number of packages placed within each canister or vault.

The waste package functions as the innermost barrier in all of the GTCC LLW disposal technologies. The function of the package is to provide total containment of the GTCC LLW (i.e., no release, for an initial period of time). The duration of the no-release period depends on the characteristics of the waste package, and its interaction with the waste and the disposal environment.

High-Integrity Containers. The NRC requires that Class B and C LLW be structurally stable prior to its disposal (NRC 1982a). Structural stability may be provided by the waste package or container. Containers approved by the NRC as meeting this requirement are generally referred to as high-integrity containers. As defined in 10 CFR 61, a structurally stable waste or, in this case, an approved high-integrity container, "will generally maintain its physical dimensions and its form under the expected disposal conditions such as weight of overburden and compaction equipment, the presence of moisture, and microbial activity, and internal factors such as radiation effects and chemical changes" (NRC 1982a). In addition, a high-integrity container should meet the requirements specified for a Type A package in 49 CFR Part 173 (CFR 1990) and 10 CFR Part 71 (CFR 1987).

The NRC's goal is that a high-integrity container should maintain its structural integrity for a minimum of 300 years (NRC 1983). The NRC has not established a requirement concerning the rate at which, or the point in time when, a high-integrity container may release radionuclides from the waste placed in it. In the absence of a requirement for acceptable radionuclide release performance for high-integrity containers, information on the three approved containers was reviewed for suitability for GTCC LLW disposal. The high-integrity containers reviewed are:

- Nuclear Packaging FL-50/EA-50
- Chichibu Steel Reinforced Polymer Impregnated Concrete
- LN Technologies Composite Stainless/Poly.

The Nuclear Packaging FL-50/EA-50 is a cylinder with a top and bottom composed of Ferralium 255. This material is a ferritic-austenitic duplex stainless steel which combines high mechanical strength, hardness, and ductility with excellent anti-corrosion properties. The container measures 119 cm (47 in.) in diameter by 129 cm (51 in.) high. The top, bottom, and sides are 1.0 cm (0.4 in.) thick; the package has an inner volume of approximately 1.3 m^3 (45 ft^3). The top of the container is equipped with a 61-cm (24-in.) diameter opening to permit loading of waste. The opening is closed with a 1.0-cm (0.4-in.) Ferralium 255 plate held in place by eight retainer blocks. A silicone rubber gasket provides the seal between the lid and the top. A lead gasket is available for especially permeable wastes, such as tritium gas and a passive vent system in the lid allows relief of pressure from gas generated by biodegradation or radioactive decay. The maximum gross weight of container and waste is 1,900 kg (4,200 lb).

The FL-50/EA-50 package is designed to be certified as a U.S. Department of Transportation (DOT) Type A container to contain waste from light water reactors, consisting of: (a) dewatered bead resins, powdered resins, and diatomaceous earth; (b) compressible solid waste; (c) noncompressible solid waste; (d) filter elements and cartridges; and (e) solidified resins, sludges, and liquid wastes. The container was considered to meet all requirements of the NRC's physical and structural tests for use in expected LLW disposal environments. Specifically, it was found that:

- The container could be expected to withstand expected LLW disposal facility loads, if the wall thickness were increased from 1/4 inch to 3/8 inch and use of four internal supports were used instead of two. None of the stresses observed in the container exceeded the 80,000 pounds per square inch yield stress of Ferralium 255.

- The thermal loads expected in LLW disposal facilities would not be likely to affect the mechanical strength of the container. Although the strength properties of Ferralium 255 decrease with increasing temperature (strength is reportedly 8.6% and 12.6% less at 200°F and 400°F, respectively, than at room temperature), temperature effects are not considered a factor in the performance of the container.

- A series of flat and corner drop tests revealed no loss of structural integrity of the container, no loss of contents, and no loss of positive seal.

- Type A package criteria (i.e., penetration, water spray, vibration, compression, and pressure tests) were all met or deemed unnecessary, based on the characteristics of the container material or the design of the container.

- The passive vent system will allow adequate release of gas resulting from biodegradation or radiolytic decay while preventing water infiltration. A lead gasket with no vent will be used when containment of tritium gas is required.

- Radiation would not be expected to affect the integrity of the container, as the package contents will not consist of significant neutron-producing materials. The non-Ferralium components (the gasket/vent materials) are not expected to show a loss of performance as a result of exposure to radiation or ultra-violet rays.

The Chichibu Steel Fiber Reinforced Polymer Impregnated Concrete container is a concrete cylinder fabricated within a carbon steel drum. Two sizes of this container, 200 L (0.2 m^3) and 400-L (0.4 m^3), are available. The 200-L unit has an inner volume of 143 L; the inner volume of the 400-L package is 285 L. The 200-L unit is 57 cm (22.4 in.) in diameter and 82 cm (32.3 in.) tall, with a minimum side wall thickness (excluding the steel drum) of 2.7 cm (1.1 in.). The minimum thickness of the lid and bottom is 3.8 cm (1.5 in.). The 200-L container weighs 172 kg (380 lb) when empty. The 400-L unit is 71 cm (28 in.) in diameter and is 104 cm (41 in.) tall, with a minimum side wall thickness (excluding the steel drum) of 3.7 cm (1.5 in.). The lid and bottom have a minimum thickness of 4.5 cm 1.8 in.). When empty, the 400-L container weighs 344 kg (759 lb).

The Chichibu high-integrity containers are fabricated by casting portland cement, aggregates, water, mixing agents, and steel fibers into the appropriate carbon steel drum. The cement is impregnated with organic monomer and polymerized to eliminate porosity within the concrete. The lid consists of the same material and is sealed to the drum walls with epoxy resin. The carbon steel drums used in the containers are equivalent to DOT 17H and 17C steel drums.

Chemical compatibility tests exposed the Chichibu containers to a pH of 0.4 to 13.5 and tested five additional classes of chemicals in power plant waste and eight chemicals found in LLW burial trench environments. No loss of compressive strength occurred for the container material, epoxy, or ceramic vent in the 1,000-hour tests. Hydrostatic testing caused failure in the lid at pressures between 1.7 and 1.9 times the maximum LLW burial depth pressure, 320 kg/m^2 (45.8 psi). The 200-L unit's body withstood pressure 18% greater than the lid, while the 400-L container did not fail at 800 kg/m^2 (114 psi), the maximum test pressure.

The LN Technologies Composite Stainless/Poly container is composed of an external stainless steel vessel, an inner lining of polyethylene, and a bottom carbon steel skirt. The head, outer lid, and shell are stainless steel; a polyethylene lining is molded into the steel vessel. The bottom skirt provides support to the vessel in the upright position and is composed of carbon steel. The polyethylene lid is the primary seal. The stainless steel lid then provides a secondary seal. The passive vent system consists of two carbon, high-efficiency particulate air filters in the polyethylene lid and stainless steel vessel neck. The body of the filter is polyethylene and the filtration material is carbon and carbon fibers.

The LN Technologies container is available in volumes ranging from 2.0 m^3 (72.5 ft^3) to 4.5 m^3 (158.2 ft^3). The smaller package is 190 cm (74.5 in.) in diameter and 101 cm (39.8 in.) tall, weighs 5450 kg (12,000 lb), and occupies a disposal volume of 2.7 m^3 (95.8 ft^3). The larger container measures 190 cm (74.5 in.) and is 184 cm (72.5 in.) tall, weighs 6,350 kg (14,000 lb), and occupies a disposal volume of 5.1 m^3 (179.2 ft^3).

Ion-exchange resins, filter sludges, and other dewatered or solidified waste are the primary waste forms intended for disposal in the LN Technologies container. The chemical resistance of polyethylene is well established; the major threat involves combined chemical and radiation exposure and induced mechanical stress. The container is designed for a pH range of 4 to 11, with a trend toward neutral. Inorganic chemicals that affect pH and conductivity do not degrade the polyethylene. Oils, toluene, ethers, and organic solvents should not be placed in contact with polyethylene. The container's temperature was cycled 30 times from -40°C to 60°C with no effect on the polyethylene. The upper and lower temperature exposure bounds for using the LN Technologies container are -29°C to 71°C.

All three containers could serve as waste packages for some or all of the identified GTCC LLW. However, there is inadequate information available in the literature regarding the long-term behavior of either the Chichibu or LN Technologies containers. It is also not known how environmental factors (e.g., corrosion) will affect their performance.

Ferralium 255, the construction material used in the Nuclear Packaging high-integrity container is most often used in marine applications; the oil, gas, and petrochemical industries; for pollution control equipment; and for other applications where high strength and corrosion resistance are especially beneficial. However, little information exists in the open literature regarding localized corrosion of base and welded Ferralium 255, the performance of this material in long-term underground applications, or the effects of potential waste stream products such as sulfonated resins, organic liquids, and chlorides on it.

While little information on the performance of Ferralium 255 is available, information is available on low-carbon austenitic stainless steels, specifically alloy 304L and 316L, that may be applicable. Ferralium 255 has a typical carbon content of 0.02%, which is less than the maximum of 0.03% used in these other low-carbon austenitic steels. Because the F255 production process reduces or eliminates nonmetallic impurities, the potential for localized corrosion using these impurities as preferential sites is greatly reduced. As a result, superior corrosion performance would be expected from Ferralium 255. Therefore, use of data based on 304L or 316L is considered to be a conservative approach to judging this material's corrosion potential.

Two types of corrosion must be considered, general and localized (pitting). General corrosion usually occurs at a fairly uniform rate over the entire exposed surface of the container and leads to complete container failure. Pitting is more difficult to predict, as pits begin and propagate at varying rates over the surface of the container. Pits generally occur at points where imperfections or impurities appear in the container surface. Pitting can be the most severe form of attack in certain cases, such as when the walls of the container are very thin. Corrosion as a result of stress-induced cracking is not considered to be as severe a consideration in these circumstances, except insofar as the cracks serve as pit initiators.

A number of studies have been conducted on the performance of stainless steels in various environments. The National Bureau of Standards conducted studies of 304 and 316 stainless steels in 15 soils over a period of 14 years. Sullivan (1991) summarizes the results as follows:

Steel (cm/yr)	Low (cm/yr)	High (cm/yr)	Mean
304	$1.1x10^{-7}$	$1.7x10^{-5}$	$5x10^{-6}$
316	$2.8x10^{-8}$	$5.7x10^{-6}$	$1.3x10^{-6}$

Beavers (1992) reported the results of long-term tests of 304L coupons in aerated, simulated Yucca Mountain well J-13 water, which is essentially pH neutral. Tests were performed using a polarization resistance measurement technique and verified by weight-loss measurements. It was found that the resistance measurement technique consistently overestimated the rate of corrosion, at later times by orders of magnitude. The average rate of corrosion over an 80-week (13,400-hour) period was measured at approximately $2.9x10^{-4}$ cm/yr.

Both long-term studies described above found that the corrosion rate decreased with increasing time. Therefore, any corrosion rate based on short-term data would necessarily be conservative in the long term.

The results of these long-term studies indicate that a general corrosion rate of $1x10^{-5}$ cm/year is appropriately conservative, as the waste packages will not be in direct contact with soil. The uncertainty associated with applying this rate to Ferralium 255, however, is not known because the actual characteristics (pH and chemical composition) of the solution contacting the container are largely unknown.

As stated above, the progression of pitting corrosion and its effect on radionuclide releases is more difficult to predict. Unlike general corrosion, pitting may occur rapidly and be very localized. A single pit may allow water to enter the container, but until other pits propagate or general failure occurs, there is no pathway for the solution to leave the container. In such a case, the container would tend to fill with water, exposing the waste to water for an extended period of time.

The effects of pitting corrosion must also be considered from the inside once the container is breached and water contacts the waste. This analysis must take into account the effect the waste form has on the container material. For example, the presence of high chloride concentrations has resulted in increased pitting of 304L samples (Thompson 1992). Thus, the dissolution of water-soluble salts such as cesium chloride (often found in sealed sources) would serve to increase the rate of attack from within the container.

When the maximum pit depth is less than the container thickness, the breached area is set equal to zero. The number of pits breaching the container is described in Sullivan (1988) as approximately 0.05 pits/cm^2 (0.05 pits/0.2 $in.^2$), based on observations of carbon steel samples. Use of the estimate of 0.05 pits/cm^2 (0.05 pits/0.2 $in.^2$) projects a total of 1,050 penetrating pits over a 0.21-m^3 (55-gallon) drum with a surface area of 21,000 cm^2 (22.6 ft^2).

The information in the literature on corrosion is useful in understanding the potential lifetime over which a stainless steel container may prevent any release of radioactivity. However, the information does not provide a basis upon which to establish a credible minimum lifetime over which high-integrity containers used for GTCC LLW disposal will prevent any release of radioactivity. The only requirement that can be applied with equal confidence to all three approved high-integrity container is the NRC design goal of 300 years. For evaluating the GTCC LLW concepts, it is assumed that the lifetimes of the high-integrity containers are distributed about this time from 200 to 500 years.

High-Level-Waste Type Containers. The NRC in 10 CFR 60 (NRC 1986) requires the high-level-waste type packages to provide substantially complete containment of the waste for a period to be determined by the NRC. This containment period is to be not less than 300 years or more than 1,000 years. The NRC further requires that the high-level-waste packages be designed to take into account the in situ chemical, physical, and nuclear properties of the waste package and its interactions with the waste and the surrounding environment. Such interactions are not to compromise the function of the waste package or the performance of the disposal facility or its geologic setting.

Based on the NRC's requirements for a high-level-waste package, the performance characteristics of the high-level waste type package for GTCC LLW were assigned. In performing the evaluation of the GTCC LLW disposal concepts we assumed that the high-level-waste type containers have lifetimes distributed between 300 and 3,000 years, with a mean value of 1,000 years.

3.3.2 Concrete Degradation and Failure Modeling

The long-term performance of the concrete canisters and vaults used in the GTCC LLW disposal concepts was modeled to determine suitable lifetime distributions for these structural components. Analyses accounted for deterioration of the concrete members of the canisters and vaults over time, and the effect concrete deterioration had upon the ability of the structures to withstand the design loads placed upon them.

Concrete degradation modeling accounted for important surface and bulk attack mechanisms. Surface attack mechanisms initiate at the surface(s) of the concrete components and progress inward over time. Notable degradation processes of this type include sulfate attack and freeze-thaw cycling. Bulk attack mechanisms modify the properties of the entire concrete component uniformly, and include the leaching of calcium hydroxide from the concrete matrix. These processes, all of which were considered in the performance modeling, are briefly described below.

Sulfate attack manifests itself in the form of expanding and cracking of the concrete. Sulfate ions from the environment diffuse into the concrete component and react with specific aluminum-containing phases in the concrete. The reaction results in internal expansion, causing stress, cracking, and exfoliation of the concrete surface.

Deterioration of damp concrete may occur when the material is subject to cycles of freezing and thawing. When water freezes in the pore system of the concrete expansive stresses develop which, if greater than the tensile strength of the material, can result in severe cracking. The susceptibility of concrete to freeze-thaw damage is, in part, a function of the material's moisture content. Generally, the concrete must be at least 70 to 80 percent saturated for freeze-thaw damage to occur (Mehta 1986).

The leaching of calcium hydroxide from the concrete results in a loss of strength in the concrete as well as a lowering of the pH of the material. The loss in strength will affect the structure's ability to bear loads placed upon it. Declines in the pH of the concrete may lead to depassivation of the steel reinforcement, thereby promoting corrosion of the steel.

In addition to the surface and bulk attack mechanisms discussed above, the corrosion of steel reinforcement in the roofs, walls, and floors of the canisters and vaults was modeled. The damage to concrete resulting from corrosion manifests itself in the expanding, cracking, and spalling of the concrete member. Structural damage may ensue due to the loss of bond between the steel and the concrete, and due to the loss of reinforcement cross-sectional area.

As a concrete structure deteriorates as a result of chemical and physical attack, its ability to bear design loads is compromised. The structure is sufficiently weakened that cracking of one or more members occurs. The time at which failure occurs may be projected based on structural and cracking analyses of the concrete canisters and vaults. Failure of the concrete structures will influence the release of radionuclides from the waste.

Long-term performance of the concrete canisters and vaults was modeled using proprietary computer codes developed by Rogers & Associates Engineering Corporation. A flow chart of the calculational methodology is presented in Figure 3-3. The analysis starts with the input of disposal site and disposal concept data that are required for the assessment. A structural analysis of the canisters or vaults is performed to establish the moments and forces placed on the various structural components.

Following the structural analysis, the codes calculate annual cycles in which the chemical and physical deterioration of the reinforced concrete is modeled. Properties of the structural members of the canister or vault are updated to reflect the effects of degradation, and a cracking analysis is performed to assess the structure's ability to bear the loads placed upon it. If the structure is able to withstand the loads, the analysis continues; if the loads exceed the bearing capacity of the structure, the time of failure is noted and the analysis ends.

Concrete degradation modeling and structural/cracking analyses were performed for the canisters in the mined cavity, drilled hole, and modular concrete canister disposal concepts at both the arid and humid sites. Separate analyses were conducted for canisters subjected to a range of loading conditions. Individual analyses were conducted for the top and bottom canisters in the mined cavity and modular concrete canister concepts. Analyses, which bound the loading conditions for all of the other canisters, were conducted for the top and bottom canisters in the drilled hole disposal concept.

The structural and cracking analyses for the concrete vaults focused on the most critical dimension of the structure. While a single analysis addressed the belowground and earth-mounded vaults, a separate analysis was necessary for the aboveground vault because of the unique conditions to which this structure is subjected.

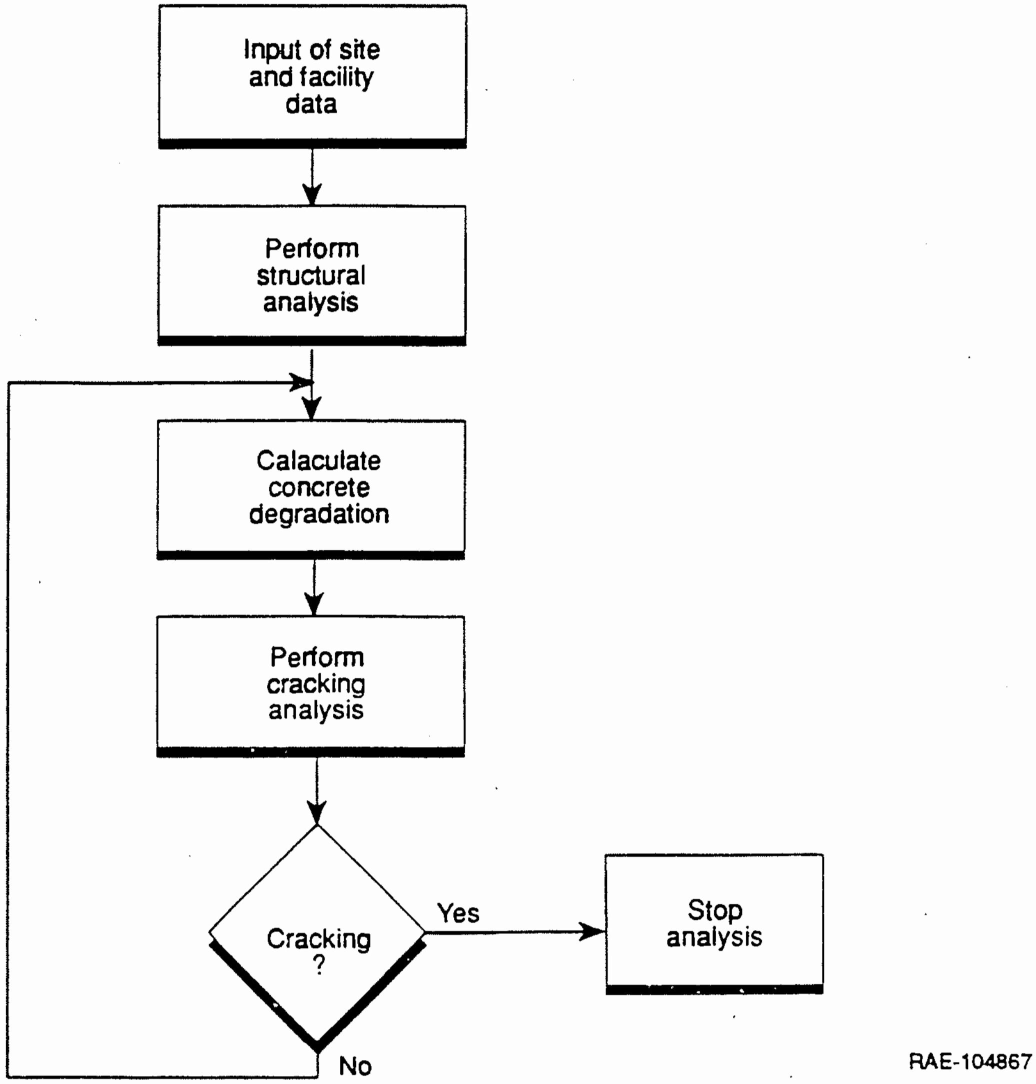


Figure 3-3. Calculational methodology for concrete degradation and cracking analyses.

3.3.3 Radionuclide Release Modeling

Radionuclides may be leached from the waste through diffusive and advective leaching mechanisms. Diffusive releases will be more significant than advective releases during the period when the concrete canisters and vaults are intact. Advective releases, which are proportional to the amount of water contacting the waste, are negligible while the canisters and vaults are intact because the low-permeability concrete excludes virtually all of the water percolating through the disposal horizon.

The release of radionuclides resulting from advection will increase in importance as the low-permeability concrete structure deteriorates. As the structure undergoes hydraulic failure resulting from cracking, greater quantities of water may percolate through the waste and leach radionuclides. Diffusive releases from the waste will also continue following failure of the canister or vault.

The rate of diffusion of radionuclides through the waste and concrete canister or vault is estimated using a time-dependent solution of Fick's law of diffusion. The canisters and vaults are modeled as a two-layer slab. The inner contaminated layer represents the stabilized waste inside the canister or vault; the initially uncontaminated, outer layer represents the wall of the canister or vault.

Diffusion coefficients were calculated as the quotient of the intrinsic diffusion coefficient and the radionuclide retardation factor. The retardation factors, in turn, were calculated using

$$R_f = 1. + \frac{\rho \, K_d}{p} \qquad \textbf{(3-1)}$$

where

R_f	=	radionuclide retardation factor in concrete/grout
ρ	=	density of concrete/grout (g/cm^3)
K_d	=	radionuclide distribution coefficient (mL/g)
p	=	porosity of grout/concrete.

Advective release rates were calculated using

$$L_a = \frac{P}{t_w (p + \rho K_d)} \qquad (3\text{-}2)$$

where

L_a	=	radionuclide release rate resulting from advection (yr^{-1})
P	=	water percolation rate through disposal horizon (cm/yr)
K_d	=	radionuclide distribution coefficient (mL/g)
t_w	=	thickness of waste (cm)
p	=	porosity of grout/concrete
ρ	=	density of concrete/grout (g/cm^3)

Radionuclide releases resulting either from diffusion or advection will be subject to availability of the waste radionuclides. Radionuclides may be unavailable for leaching if the high-integrity or high-level-waste type container is intact, or if the radionuclides are contained within the stainless steel jacket of a sealed source. Once these containers or jackets are compromised, releases resulting from diffusion and/or advection are possible.

Release rates from activated metals as a result of diffusion or advection may be limited by the rate at which the activated metal components corrode. Projected diffusive and/or advective release rates will apply to the extent that they do not exceed the rate at which radionuclides are mobilized from the metal components as a result of corrosion. If the rate of mobilization from corrosion is less than the projected diffusive and/or advective release rates, the release is simply equal to the corrosion rate.

All scenarios involving groundwater are modeled using a Darcian flow system. The groundwater transport pathways all involve a vertical and a horizontal leg. In the case of an unsaturated site, the vertical leg is from the disposal horizon down to an underlying aquifer. For cases where the site is saturated, the vertical leg may be either downward or upward, depending on the specific site conditions. For the near-surface facilities analyzed, the vertical leg is downward to an underlying aquifer. For the intermediate-depth and deep geologic concepts, the vertical leg is upward to an aquifer that in not the water table aquifer. For all cases, the horizontal leg is the transport in the aquifer from the edge of the disposal horizon to the accessible environment.

The five parameters needed to predict Darcian flow are hydraulic conductivity, porosity, hydraulic gradient, flow distance, and cross-sectional area. Travel time is defined by:

$$T = (d\ p) / (i \cdot K) \qquad \textbf{(3-3)}$$

where

T	=	the fluid travel time (years)
d	=	the length of the leg (meters)
p	=	the effective porosity
i	=	the hydraulic gradient
K	=	the hydraulic conductivity (meters/year).

Volumetric flow of water is found by:

$$V = Ki \cdot A \qquad \textbf{(3-4)}$$

where

V	=	the volumetric flow (cubic meters/year)
K	=	hydraulic conductivity (meters/year)
i	=	hydraulic gradient
A	=	the cross sectional flow area (square meters).

Normal groundwater flow refers to the movement of water through the depth where the disposal facility is located, according to the natural hydrologic conditions, perturbed to some degree by the presence of the facility. During the construction and operation of the facility, water in the surrounding media would be expected to gradually drain so that the media will enter an unsaturated condition near the openings. After the end of the operational period and closing of the facility, water would be expected to gradually seep back into pores and fractures in the rock and establish a flow regime connected to the regional groundwater system.

The resulting flow patterns may be different from those prior to the excavation of the facility. For example, the heat generated by the waste may modify the hydraulic conductivity of the surrounding media and may also change the properties of water, making it less dense and less viscous. The lower density can lead to a buoyancy effect that may cause an increased vertical hydraulic gradient. The decreased viscosity may enable the water to flow more easily through the rock, thereby allowing for potential increases in flow rates.

Facilities in basalt or granite will eventually become saturated if the repository is located below the water table. For these cases, natural heat driven hydraulic gradients cause normal groundwater flow to be upward through the host rock to an overlying aquifer.

Upward vertical gradients result from pressure differences between upper and lower aquifers. Upward vertical gradients may also result from thermal buoyancy effects, as a result of the heat generated by the emplaced waste (EPA 1982).

For a facility in volcanic tuff, normal groundwater flow refers to the downward percolation of water through the unsaturated rock toward the water table. This downward movement is not expected to be influenced by the presence of the repository, because the flow is limited by the amount of water available.

Inadvertent Intrusion. The potential and consequence of intrusion into GTCC LLW placed in each disposal technology are assessed in two steps. First, based on the characteristics of the disposal concept, intrusive events which could occur are identified from the range of such events. Second, for those events that are probable, a quantitative estimate of the impact of the event is calculated. REPRISK (Smith 1982), a code developed to calculate the consequence of disruptive events, is used for the quantitative assessment.

3.4 Sensitivity Analysis

3.4.1 Concrete Degradation Sensitivity Analysis

Concrete degradation and cracking analyses were conducted for the canisters and vaults for the design loading conditions and expected environmental conditions at the arid and humid disposal sites. In addition, the sensitivity of the canister and vault lifetimes to changes in selected parameters was investigated to permit estimation of an appropriate lifetime distribution for each disposal concept. The approach taken in this sensitivity analysis is discussed below.

The ability of the concrete canisters and vaults to minimize releases of radionuclides to the environment is largely a function of their ability to exclude water from the waste. While the intact concrete structures will effectively prevent water from contacting the waste, because of the low permeability of the concrete, failure of the structures as a result of cracking may be expected to permit greater rates of infiltration through the waste. Increased rates of release of waste constituents will accompany these higher rates of flow.

The concrete canisters and vaults were designed to bear anticipated loads, minimizing percolation of water through the waste for extended periods of time at the two types of disposal sites. Failure times for the concrete structures, however, will be affected by changes in the loading conditions and changes in rates of concrete degradation. In recognition of this fact, canister and vault performance was examined for more aggressive conditions, referred to as "high-exposure" conditions, in addition to the nominal or "base-case" conditions.

The sensitivity of canister and vault lifetimes to high-exposure conditions was examined by modifying the loading conditions, the chemical environment, and the diffusive properties of the concrete. Loads placed on the structures were increased by 20%; groundwater concentrations of aggressive ions (i.e. Cl^-, CO_3^-, Mg^{2+}, and SO_4^{2-}) were increased; and concrete diffusion coefficients for chloride and sulfate ions were reduced by one order of magnitude. These changes have the effect of placing greater structural demands on the canisters and vaults, while hastening the rate at which the concrete deteriorates.

The results of the base-case and high exposure conditions model runs were used to estimate lifetime distributions for concrete canisters and vaults for each disposal concept at each site. Canister lifetimes were assumed to be distributed between the year in which the canister subjected to the greatest load failed under the high-exposure conditions and the year the canister bearing the smallest load failed under the base-case exposure conditions. Vault lifetimes were assumed to be distributed between the year the vault failed under high-exposure conditions and the year the vault failed under base case conditions. The specific lifetime distributions used for the canisters and vaults within the range defined by the case-case and high-exposure conditions are explained in Section 5.

3.4.2 Sensitivity Analysis of Radionuclide Release Rates

The rate radionuclides are released from the waste as a result of diffusion and advection depends, in part, upon the distribution coefficient. Radionuclide distribution coefficients for grout and concrete are influenced by numerous factors, among them the chemical form of the radionuclides and the chemistry and pore structure of the grout/concrete. Recognizing the high degree of uncertainty inherent in radionuclide distribution coefficients for these materials, a range of coefficients was used in modeling radionuclide releases from the stabilized waste. Release rates resulting from diffusion and advection were assumed to be uniformly distributed between the rates calculated using the high and low coefficients for each radionuclide.

4. CHARACTERISTICS OF GTCC LLW DISPOSAL CONCEPTS

In order to conduct the technical evaluation of the GTCC LLW disposal concepts, each concept must be fully characterized. As part of this characterization, the types and quantities of GTCC LLW requiring disposal, the performance specifications of the waste packages, the design information for the concrete canisters and vaults, and important features of the disposal environment must be specified.

The data used to describe these aspects of the disposal concepts are presented in this chapter. The projected volumes and activities of GTCC LLW requiring disposal are provided in Section 4.1. Performance characteristics of the high-integrity and high-level-waste type containers are considered in Section 4.2. Design information for the various disposal concepts are provided in Section 4.3. Site characterization data for the arid and humid sites are given in Section 4.4.

4.1 GTCC LLW Characterization

This section characterizes the types and amounts (volumes and activities) of waste that can be expected to be disposed of as GTCC LLW. The document Greater-Than-Class C Low-Level Radioactive Waste Characterization: Estimated Volumes, Radionuclide Activities and Other Characteristics (DOE 1991c) is the primary source of information for the characterization. The report provides projections of waste volumes and radionuclide-specific activities based on specific studies of potential GTCC waste streams and past surveys of potential generators of GTCC LLW. The document Evaluation of Department of Energy-Held Potential Greater-Than-Class C Low-Level Radioactive Waste (DOE 1992b), which details potential commercial GTCC LLW presently stored by DOE, is also used in the characterization effort.

The characteristics of the GTCC LLW are important to the performance of the various disposal concepts in several ways. The overall volume of GTCC LLW determines the amount of disposal capacity required, which in turn defines the size of the facility. The size of the facility and other site characteristics determine the amount of water that may interact with the waste. The specific radionuclides present, and the activity associated with each, play a role in defining potentially important exposure pathways. Finally, the type of waste, its physical characteristics, and the material(s) it is composed of are important in determining the rates and mechanisms of radionuclide release.

GTCC LLW is categorized by source as nuclear utilities waste, sealed source waste, DOE-held potential GTCC waste, and other generator waste (DOE 1991c). Review of this information shows that, regardless of the source of the GTCC LLW, it may be divided into categories based on the physical form or release characteristics of the material. For the technical feasibility study, four categories were chosen. These categories and their distinguishing characteristics are as follows.

GTCC LLW category	Characteristics
Activated metals	The radioactivity is distributed throughout the metallic waste material and is typically a result of irradiation. Release of the radioactivity from the waste occurs as the metal corrodes. If the release rate due to corrosion is large enough, the release to the environment is limited by leaching.
Process waste	The radioactivity is contained on or in ion-exchange media, filter media, cartridge filters, or other substances and devices used to remove and concentrate radioactivity from liquids and other wet wastes. The radioactivity is released from the waste by leaching, diffusion, or dissolution.
Contaminated equipment and material	The radioactivity is primarily the result of surface contamination on either internal or external surfaces of equipment and other contaminated objects. The radioactivity is released from the waste due to leaching, diffusion, or dissolution.
Sealed sources	The radioactivity is contained inside a nonradioactive metal jacket. The jacket, while intact, contains the radioactivity and prevents any release. After the jacket corrodes or is penetrated by other means, the radioactivity may be released as a result of leaching, diffusion, or dissolution.

Based on these four GTCC LLW categories, the information on GTCC LLW characteristics found in the cited reports (DOE 1991a and DOE 1991b) was examined and reorganized to produce the individual waste category inventories and total waste inventory used in the technical evaluation.

The volume and activity data reported for each category of GTCC LLW are based on information obtained by EG&G Idaho, Inc., from generators of GTCC LLW and on information gained through discussions with the authors of DOE/LLW-114 (DOE 1991c). The largest volumes and activities of GTCC LLW are expected to result from nuclear utility operations and decommissioning. The NRC surveyed manufacturers and users of sealed sources to determine the number and types of sources that may require disposal as GTCC LLW. Other generators (e.g. research facilities) were interviewed for potential

GTCC LLW. Finally, EG&G Idaho, Inc., developed an inventory of potential GTCC LLW currently held by DOE.

The potential GTCC LLW was distributed as accurately as possible throughout the four waste categories described above. The largest degree of uncertainty in the characterization of the waste is associated with the DOE-held GTCC LLW, because activity data for a significant portion of the waste are unavailable. Information on waste from other generators was obtained through the 1986 Energy Information Administration survey.

In projecting the generation of GTCC LLW, DOE/LLW-114 (DOE 1991c) considered the necessity of packaging the waste for shipment and disposal. Three possibilities were developed to determine the effects of packaging on generated volumes. Volumes were projected using unpackaged volumes (waste as generated); packaged volumes, based on the application of packaging factors to the unpackaged volumes (which takes into account any predisposal treatment or packaging); and concentration averaging over the packaged volumes (which combines similar materials and averages the activities over the waste or container volumes). Concentration averaging can actually result in smaller volumes of GTCC that require disposal, because the average over the waste or container volume may be within Class C limits. Much of the waste reported by other generators and DOE-held potential GTCC LLW is already packaged; adequate information on the unpackaged volumes or concentration averaging for these wastes was not available. Information was also unavailable regarding concentration averaging for sealed sources.

Each of the three packaging possibilities was considered using low, base, and high estimates of volume. The base-case data were obtained through surveys and reflect current practices in management, packaging, and concentration averaging (those employed at Barnwell, South Carolina). The low-case data represent the lower end of the base case, taking into account more efficient packaging and less strict concentration averaging procedures (those employed at Richland, Washington). The high estimate data were achieved through assumptions regarding reactor lifetimes, the amount of decommissioning waste that would exceed Class C limits, more stringent concentration averaging, and the use of higher packaging factors.

All data provided in this section reflect projections for the base case to the year 2035, using packaged volumes. The base case most closely reflects the present state of waste management and is, therefore, the most realistic estimate of future disposal capacity requirements. Packaged volumes are used as the conservative case, because they have the most information available across the range of wastes and resulted in the highest estimates of volume for the base case.

Of the 3.25E+03 m^3 (1.15E+05 ft^3) of waste reported for the base-case packaged amount of GTCC LLW in DOE/LLW-114, 3.20E+03 m^3 (1.13E+05 ft^3) was assigned to the four waste categories. A total of 5.41E+07 Ci of the total base-case activity reported in DOE/LLW-114 was assigned to the four waste categories. The majority of the 1.17E+07 Ci that was not assigned to a category (6.73E+06 Ci) was identified by the authors of DOE/LLW-114 as a possible overestimate of transuranic (TRU) activity in utility-generated activated metals. The remaining 50 m^3 (1.87E+03 ft^3) and 4.97E+06 Ci were not considered in the technical evaluation of the GTCC LLW disposal concepts. The volumes and activities reported in DOE/LLW-114 which were not included in the analysis of GTCC LLW disposal concepts are summarized in Table 4-1.

4.1.1 Activated Metals

Activated metals are produced by nuclear utilities and other waste generators, primarily sealed-source manufacturers. Nuclear utilities produce a range of specific wastes that are categorized as activated metals. For projection purposes, these components were considered as either operations waste or decommissioning waste. Operations waste that is routinely generated as GTCC LLW includes items such as control rod blades and thimble plug assemblies. Base-case decommissioning waste consists of core shrouds. Core barrels from pressurized water reactor decommissioning were not included in projections for the base case because it was not clear that they would be GTCC LLW (DOE 1991c).

Activated-metal components that will be routinely generated and categorized as potential GTCC LLW by the utilities include the following:

Boiling water reactors	Pressurized water reactors
Operations Waste	Operations Waste
Control rod blades	Thimble plug assemblies
Local power range	In-core detectors and instrument strings
Intermediate & source range	
Monitoring instruments, dry tubes	
Decommissioning Waste	Decommissioning Waste
Core shroud	Core shroud

Table 4-1. Volumes and activities of GTCC LLW considered in the disposal concept analysis.

	Volume (m^3)	Activity (Ci)
Amount identified in DOE/LLW-114	3.25E+03	6.58E+07
Amount considered in disposal concept analysis	3.20E+03	5.41E+07
Amount not considered in disposal concept analysis	5.00E+01	1.17E+07

In addition to the items listed above, other reactor waste items are listed in the 1986 Energy Information Administration survey, including poison curtains and control rod bearings. These items are included in the activated metals waste category. The projections analysis carried out in DOE/LLW-114 produced the results shown in Table 4-2 for the base case, projected to the year 2035 using packaged volumes.

Waste in addition to that listed for the utilities was assigned to the activated-metals waste category. This waste included a portion of the DOE-held GTCC LLW, which was difficult to classify because of a lack of information. Metal waste from other generators was also assigned to the category.

A total waste volume and activity of 1.59E+03 m^3 (5.61E+04 ft^3) and 3.72E+07 Ci, respectively, were assigned to the activated-metals category. This volume represents 49.6% of the total base-case GTCC LLW volume; the activity is 68.8% of the total GTCC LLW activity. Utilities account for more than 99% of the activated waste by volume and activity. Approximately 8 m^3 (282 ft^3) and 1.25E+02 Ci of activated-metal waste were identified as coming from other waste generators.

The radionuclide-specific activities for the activated-metals waste category are provided in Table 4-3. As discussed earlier, 6.73E+06 Ci of the TRU activity reported in DOE/LLW-114 for activated metals was a possible overestimate by the reporting generator. Assignment of the remaining 1.77E-01 Ci of TRU activity based on discussions with the authors of DOE/LLW-114 resulted in activities 1.27E-01 Ci for Pu-239 and 5.01E-02 Ci for Am-241. This TRU activity is present as surface contamination.

The radionuclides present in the greatest activities are Co-60, Ni-63, and Fe-55. These three radionuclides, all with half lives of fewer than 100 years, represent over 99% of the total activity. The five radionuclides with half lives greater than 100 years (C-14, Ni-59, Nb-94, Tc-99, and Am-241) account for 1.77E+05 Ci, or less than one half of one percent of the assigned activated-metal activity.

As discussed earlier, the majority of the activity assigned to the activated-metals category will be mobilized as the metal components corrode. In modeling releases resulting from corrosion, a corrosion rate of 1.0E-05 cm/yr was assumed. This corrosion rate is based on data for 304 stainless steel (see discussion in Section 3.3.1), of which the majority of activated-metal wastes are composed. Because of the surficial nature of the TRU contamination of the activated-metal waste, releases of Pu-239 and Am-241 are assumed to occur as a result of dissolution and subsequent diffusive and/or advective leaching.

Table 4-2. Utility activated-metal waste characteristics.

Component	Volume (m^3)	Activity (Ci)	Predominant radionuclides
<u>Boiling Water Reactor</u>			
Control rod blade	4.41E+02	1.62E+05	Ni-63(59%), Co-60(33%)
Local power range monitor	9.67E+01	6.65E+04	Ni-63(50%), Co-60(18%)
Dry tubes	2.13E+01	1.08E+05	Ni-63(71%), Co-60(24%)
Control rod bearings	1.42E-04	8.93E+00	Ni-63(57%), Co-60(43%)
Poison curtains	6.78E-03	1.55E+02	Ni-63(98%)
Core shroud	2.57E+02	4.93E+06	Ni-63(46%), Co-60(38%)
SUBTOTAL	8.16E+02	5.27E+06	
<u>Pressurized Water Reactor</u>			
Thimble plug assemblies	7.79E+01	1.66E+04	Ni-63(70%), Co-60(23%)
In-core detectors	4.10E+01	1.40E+05	Ni-63(70%), Co-60(25%)
Instrument strings	4.59E+01	2.39E+04	Ni-63(77%), Co-60(22%)
Control rod drive	1.80E+02	2.77E+04	Ni-63(98%)
Flux wire	4.60E-01	1.55E+04	Ni-63(99%)
Miscellaneous metals	1.59E+00	No data	No data
Core shroud	2.66E+02	3.17E+07	Co-60(50%), Fe-55(26%)
SUBTOTAL	4.51E+02	3.72E+07	
TOTAL	1.27E+03	4.25E+07	

Table 4-3. Radionuclide distribution in activated metals.

Radionuclide	Activity (Ci)
Am-241	3.40E+01
C-14	4.35E+04
Co-60	1.80E+07
Cs-137	8.31E+03
Fe-55	9.21E+06
H-3	5.26E+03
I-129	1.00E+00
Mn-54	2.00E+04
Nb-94	6.39E+02
Ni-59	1.31E+05
Ni-63	9.81E+06
Pu-238	4.90E-01
Pu-239	2.37E+03
Pu-240	0.00E+00
Pu-241	1.79E+01
Sr-90	7.35E+03
Tc-99	2.37E+03
TOTAL	3.72E+07

4.1.2 Process Wastes

Process wastes are generated by the cleanup of liquids containing radioactive constituents. Wastes in this category include ion-exchange media, filter media, and cartridge filters. The radionuclides of concern in classifying this waste are Cs-137 and Sr-90, with Ni-63 a consideration for the cartridge filters. Process waste is generally considered to be the result of operations, not decommissioning. The results of the projections reported in DOE/LLW-114 are shown in Table 4-4.

A volume of 1.13E+03 m^3 (4.01E+04 ft^3) and an activity of 5.04E+05 Ci were assigned to the process waste category. This waste represents 35.5%, by volume, of the total projected GTCC LLW and just under one percent of total GTCC LLW activity. Utilities account for 51.1% of the process waste by volume and just over 5% of the activity. Other waste generators are responsible for about 8.25E+01 m^3 (2.92E+03 ft^3) of the process waste and an activity of 1.02E+02 Ci. This represents about 7% of the volume and less than 1% of the activity of the process waste category. The process waste held by DOE accounts for the remaining 4.75E+02 m^3 (1.68E+04 ft^3) and 4.77E+05 Ci, or 42% and over 94%, respectively, of the category totals.

The radionuclide distribution of the process-waste category is provided in Table 4-5. The nuclear utilities reported TRU activity totaling 1.37E+02 Ci, which was assigned as 1.26E+02 Ci of Pu-239 and 1.09E+01 Ci of Am-241. This distribution was based on reactor type, consistent with discussions with the authors of DOE/LLW-114 (DOE 1991c). Approximately half of the activity reported by other generators was also listed as TRU. This activity was reported by sealed-source manufacturers and was assigned as Am-241, Pu-238, and Pu-239. The activity assigned to each radionuclide was in proportion to the amount reported for sealed sources by sealed-source manufacturers. The activity associated with the DOE-held Three Mile Island process waste is a mixture of cesium and strontium. While the activities of the specific isotopes were not reported, the activity was assigned as 60% Cs-137 and 40% Sr-90 based on discussions with persons at EG&G Idaho, Inc., who are familiar with the waste.

The predominant radionuclides in the process GTCC LLW are Co-60, Cs-137, and Sr-90. These three radionuclides, all with half lives equal to or less than 30 years, represent over 98% of the total activity. The seven radionuclides with half lives greater than 100 years (C14, Ni-59, Nb-94, Tc-99, I-129, Pu-239, and Am-241) account for 6.44E+02 Ci or about 0.1% of the total waste category activity.

Table 4-4. Utility process waste characteristics.

Component	Volume (m^3)	Activity (Ci)	Predominant Radionuclide
Decontamination Resins	2.73E+02	2.55E+04	Co-60(64%), Ni-63(20%)
Pool Filters	3.36E+01	2.00E+02	Ni-63(67%), Co-60(20%)
Control Rod Drive Strainers (outer)	2.22E+01	6.76E+01	Co-60(28%), Fe-55(19%)
Control Rod Drive Strainers (inner)	5.09E-01	6.85E+01	Co-60(26%), Fe-55(19%)
Cartridge Filters	2.43E+02	7.30E+02	Ni-63(84%), Co-60(8%)
Crud Tank Filters	4.64E+00	3.47E+01	Ni-63(82%), Co-60(10%)
TOTAL	5.77E+02	2.66E+04	

Table 4-5. Radionuclide distribution in process wastes.

Radionuclide	Activity (Ci)
Am-241	1.55E+02
C-14	3.13E+02
Ce-141	6.01E+01
Ce-144	3.07E+00
Cm-242	1.60E-03
Co-58	5.69E-04
Co-60	1.64E+04
Cs-134	1.28E+01
Cs-137	2.87E+05
Fe-55	2.33E+03
H-3	1.69E+00
I-129	2.00E+00
Mn-54	4.42E+00
Nb-94	7.59E-04
Ni-59	2.13E+00
Ni-63	5.87E+03
Pu-238	2.53E+00
Pu-239	1.69E+02
Pu-241	6.41E+02
Sr-90	1.91E+05
Tc-99	2.73E+00
Zn-65	3.35E-01
TOTAL	5.04E+05

4.1.3 Contaminated Equipment and Material

Contaminated solids are common at most facilities that use or process radioactive materials. They typically consist of paper, plastics, wood, cloth, and other ordinary trash. The radioactivity is generally present as transuranic radionuclides and is typically present as surface contamination. A typical waste stream in this category would be glove boxes from fuel fabrication or uranium processing facilities.

A total volume of 1.99E+02 m^3 (7.04E+03 ft^3) and activity of 2.87E+03 Ci were assigned to the contaminated-equipment and material category. The waste represents 6.2%, by volume, and much less than one percent, by activity, of the GTCC LLW considered in the technical evaluation. Other generators account for 88.4% of the contaminated equipment and materials by volume and 82.3% of the activity. Waste held by DOE accounts for the remaining 2.33E+01 m^3 (8.24E+02 ft^3) and 5.07E+02 Ci.

The radionuclide distribution of the contaminated-equipment and material category waste is given in Table 4-6. The waste reported for sealed-source manufacturers listed activity totaling 1.03E+03 Ci as TRU, specific isotopes were not listed. This activity was apportioned as 5.05E+02 Ci of Pu-238, 2.06E+01 Ci of Pu-239, and 5.05E+02 Ci of Am-241, based on the distribution of activity of these radionuclides in other waste streams from the same generators. The DOE-held contaminated equipment and materials are not well characterized. The 5.07E+02 Ci reported were listed as a mixture of americium and plutonium; specific isotopes were not reported. Based on discussions with personnel at EG&G Idaho, Inc., who are familiar with this waste, the activity was assigned as 95% Pu-239 and five percent Am-241.

The dominant radionuclides found in contaminated equipment and materials all have half lives greater than 100 years. Four radionuclides (Pu-238, Pu-239, Pu-241, and Am-241) account for over 99% of the total activity for this waste category.

4.1.4 Sealed Sources

Sealed sources typically consist of one or two radionuclides at fairly high activities enclosed in a casing or jacket, usually made of stainless steel. Sources are used in a wide variety applications, including well logging devices, X-ray fluorescence, moisture gauges, beta and gamma gauges, and calibration devices.

Table 4-6. Radionuclide distribution in contaminated equipment and material.

Radionuclide	Activity (Ci)
Am-241	1.68E+03
Cs-137	6.85E+00
Pu-238	5.05E+02
Pu-239	5.02E+02
Pu-241	1.83E+02
Sr-90	2.98E-04
TOTAL	2.88E+03

The sealed-sources waste category includes a relatively small number of different isotopes. Throughout the 1960s and early 1970s, cesium, in the form of cesium chloride, was the dominant radionuclide source. Sources used in moisture/density gauges and well logging devices typically include Cs-137, Pu-238, and/or Am-241. Sealed sources from pressurized-water reactors consist of neutron source material that is encapsulated in stainless steel and usually located in a burnable-rod assembly. The source material is commonly plutonium or americium, depending upon the manufacturer.

Sealed sources occur in a variety of sizes. A moisture/density gauge is typically 1.0 cm (0.4 in.) in diameter and 1.5 cm (0.6 in.) long, with a volume of 1.2 cm^3 (0.1 $in.^3$). In comparison, a well logging source is substantially larger, measuring 2.5 cm (1 in.) in diameter and 7.5 cm (3 in.) long, with a volume of 38.6 cm^3 (2.4 $in.^3$).

The source generally occupies a small volume compared to the entire instrument, especially when packaged for shipment and disposal. The moisture/density gauge with a sealed source of 1.2 cm^3 volume may be surrounded by shielding, with a volume of 4.0E+03, and placed in a gauge with a total volume of 1.5E+04. When packaged for disposal, the total volume may increase to 1.0E+05. Although most sources are stored with the instrument as a single component, it is likely that the sealed source will be removed from the instrument and disposed of separately.

A total volume of 2.78E+02 m^3 (9.84E+03 ft^3) and activity of 1.64E+07 Ci are assigned to GTCC LLW sealed sources. Ninety-six percent of the waste category volume is accounted for by sealed sources held by DOE. Almost all of the DOE held sealed sources consists of plutonium nitrate sources used in fuel production research. Sealed sources from other generators and utilities account for 3.6% and less than 1% of the waste category volume, respectively. In terms of activity, however, utilities contribute more than 95% of the category total, 1.60E+07 Ci, while other generators contribute 3.23E+05 Ci or almost two percent. The DOE-held sealed sources account for the remaining 6.00E+04 Ci, about 0.3% of the total.

The radionuclide distribution of the sealed sources GTCC LLW is provided in Table 4-7. With the exception of Am-241, Pu-239, and Pu-240, all of the radionuclides listed have half lives of fewer than 100 years. The three longer lived radionuclides account for 1.60E+07 Ci, or more than 98% of the total activity.

Table 4-7. Radionuclide distribution in sealed sources.

Radionuclide	Activity (Ci)
Am-241	3.14E+04
Cs-137	2.81E+05
Cm-244	2.00E+03
Pu-238	1.97E+04
Pu-239	1.61E+07
Pu-240	5.55E+00
Pu-241	6.03E+01
Sr-90	1.00E-02
TOTAL	1.64E+07

The release characteristics of the isotopes used in sealed sources depend on the matrix in which they are bound and the type and thickness of the jacket surrounding the radioactivity. Information on the manner in which some of these sources are fabricated is provided below.

Stated earlier, cesium chloride sources have been in use since the 1960s. However, it was found that the solubility of cesium chloride in water (162 g/mL cold water, 260 g/mL hot water) posed a serious problem should the capsule be breached. In some cases, a damp environment could contribute to the degradation of the capsule from the inside, because the presence of chloride causes increased pitting of 304 stainless steel. As a result, other methods of fabricating cesium sources have been developed. These other sealed sources use the cesium in its natural form, either bound into a quartz-like material or soaked into an inert resin and fired.

While other methods of cesium source manufacturing have been developed, cesium chloride sources are still in use because they provide higher specific activities than other sources. The cesium chloride is generally bound into another medium to reduce the potential for release. In some medical applications, the source consists of a porous glass material soaked in cesium chloride and fired. Cesium chloride may also be bound into a ceramic enamel casing, which is non-porous, insoluble, and non-leaching. Should these binding media fail completely, however, the cesium chloride would still be released, posing the same threat of corrosion to metal components.

Americium sources have become more widespread as a result of the increased availability of americium since the mid-1960s. These sources generally take the form of americium dioxide, which is very dense and nearly insoluble in water. The americium dioxide is pressed into a pellet by pressures up to 10 tons, depending on the size of the source. The sources may also be incorporated into a ceramic enamel matrix, as described above in connection with cesium sources.

The most common plutonium sources use the dioxide form of Pu-238 and are fabricated in much the same way as americium sources. Pu-239, however, presents more difficulty in handling, as it is an ignitable metal. Pu-239 sources are generally prepared by sintering and firing. They may then be incorporated into a binding matrix, as discussed previously.

Currently produced sources are now routinely double-encapsulated with stainless steel to provide further resistance to releases. The thickness of the encapsulation depends on both the size and intended use of the source. For example, well-logging sources must be able to withstand higher pressures than other sources. One manufacturer of sources for well-logging applications requires a minimum capsule thickness of 0.1 cm (0.04 in.) for each layer, with thicker capsules for larger sources. The same manufacturer requires 0.3 cm (0.1 in.) thickness for standard 20-Ci americium sources. In general, a standard stainless steel such as 304 or 316 is employed for the capsule, although well-logging sources may use a stainless steel that displays less sensitivity to pressure, such as 17/4.

Because no viable disposal mechanism for sealed sources has existed, there is no reliable information concerning the age of many of the existing sources or on the condition of their metal jackets. For the technical evaluation of the GTCC LLW disposal concepts, a 2-cm (0.8-in.) thick jacket made of 304 stainless steel is assumed. This jacket is assumed to corrode at a rate of 1.0E-05 cm/yr (3.9E-06 in./yr), consistent with the discussion on corrosion rates in Section 3.3.1.

4.2 GTCC LLW Package Performance Characteristics

The performance characteristics of the high-integrity and high-level-waste type containers were discussed in Section 3.3.1. As stated in that discussion, available information does not provide a reliable basis upon which a credible lifetime for high integrity containers can be based. In terms of the high-level-waste type containers, little is known regarding credible lifetimes.

In the absence of data on credible container lifetimes, lifetimes for the high-integrity and high-level-waste type containers were based on regulatory requirements for the technical evaluation of the GTCC LLW disposal concepts. In terms of the high-integrity container, it was assumed that the mean lifetime was 300 years, consistent with the NRC's design goal for this package. Package lifetimes were distributed about this mean value from 200 to 500 years, using a log-normal distribution.

The mean lifetime of the high-level-waste type package was assumed to be 1,000 years, consistent with the maximum lifetime required by the NRC in 10 CFR 60 (NRC 1982a). Container lifetimes were assumed to be distributed log-normally between 300 years, the minimum required lifetime, and 3,000 years.

4.3 Characteristics of the GTCC LLW Disposal Concepts

Development of the conceptual designs of the GTCC LLW disposal concepts requires an understanding of the requirements and features each concept must address or include. To ensure consistency in the evaluation of the disposal concepts, it is necessary to ensure that each concept is designed to a common set of standards. A design basis, therefore, was developed and addresses the regulatory requirements, essential features, and common design standards.

The regulatory requirements that may be expected to apply to the design and construction of the GTCC LLW disposal concepts are considered in Section 4.3.1. The design features and standards of the disposal concepts, based in part on the regulatory requirements, are discussed in Section 4.3.2. The general concept description is provided in Section 4.3.3; specific design information for the GTCC LLW disposal concepts is provided in Section 4.3.4.

4.3.1 Regulatory Requirements

The NRC has declared that GTCC LLW is not suitable for disposal in a near-surface facility unless specifically approved by the NRC. In instances where a high-level waste repository is not used, it is the NRC's position that the containment requirements for the GTCC LLW would be the same as those for a repository, unless lesser requirements proved sufficient. Of the requirements contained in 10 CFR 60, some apply to the waste, others apply to the disposal site, and still others to the facility. Questions, therefore, remain about the regulatory requirements that might be applied to the GTCC LLW disposal concepts.

It is reasonable to expect the regulations that will apply to the disposal of GTCC LLW will be bounded by the existing NRC regulations for LLW (10 CFR 61) and high-level waste (10 CFR 60). Each of these regulations states siting, design, and other criteria that can be useful in determining a set of regulatory requirements that might reasonably be applied to the disposal of GTCC LLW. The regulatory requirements can, in turn, be related to required functions that any GTCC LLW disposal concept must perform. These functions are fundamental to the successful performance of the disposal system and are referred to as "required functions." The required functions for all the disposal concepts, or to which the concepts must contribute, for either low-level or high-level waste, are summarized as follows:

- Protect the general population from releases of radioactivity (10 CFR 61.41 and 10 CFR 60.113)

- Protect individuals from inadvertent intrusion (10 CFR 61.42)

- Protect individuals during operations (10 CFR 61.43 and 10 CFR 60.111)

- Ensure stability of the disposal site after closure (10 CFR 61.44 and 10 CFR 60.133)

- Minimize waste in contact with standing water (10 CFR 61.51, 10 CFR 60.133, and 10 CFR 60.134)

- Stabilize the waste form (10 CFR 61.56 and 10 CFR 60.135)

- Ensure structurally stable waste packages (10 CFR 61.56 and 10 CFR 60.113)

- Maintain retrievability option (10 CFR 60.111).

4.3.2 Design Features and Standards

The design features and standards are developed based on the regulatory requirements applicable to the GTCC LLW disposal concepts, the assumed site characteristics, and the estimated volumes and activities of the GTCC LLW requiring disposal. These are discussed in terms of general facility considerations, disposal unit design features, design considerations for concrete structures, special requirements for aboveground vaults, engineered cover systems, surface-water management, design considerations for shafts and mines, and radiological safety.

General Facility Considerations. The disposal facility is assumed to have adequate capacity to accommodate all GTCC LLW projected to be generated from nuclear utilities and other generators. The development of the disposal facility is assumed to require 10 years, during which time the site selection, site characterization, and engineering design are completed. The support facilities and disposal structures are constructed in the last three years of the preoperational period. Necessary Federal licenses and state and local permits are issued by the end of this development period. All projected GTCC LLW will be disposed of between the years 2035 and 2055. The disposal site will be stabilized and closed in about two years. The permanent disposal facility will be monitored for 100 years following its closure.

The surface land area occupied by the facility is sufficient to accommodate the administrative area, the general support area, the waste disposal units, and a buffer zone. The outer limits of the buffer zone shall be designated by a security fence. The general support area is located within an inner fence. Access to the waste disposal area is controlled with passive and active systems, and is restricted to those with a legitimate need to be present and who are appropriately monitored for radiation exposure. The administrative area lies outside the inner fence.

Disposal Unit Design Features. The disposal units are designed to satisfy the following functional requirements:

- Provide sufficient space for disposal of all GTCC LLW

- Contain the waste without loss of structural integrity for at least 200 years, giving consideration to the chemical characteristics of the waste, backfill material, and materials used in construction of the disposal unit

- Complement and improve the ability of the natural site to accomplish the performance objectives

- Minimize, to the extent practical, the potential for contact between waste and water both during and after disposal operations

- Minimize voids between waste containers in the disposal unit

- Eliminate, to the extent practical, the need for ongoing active maintenance of the disposal unit following closure (only surveillance, monitoring, and minor custodial care are required after the disposal facility is closed)

- Permit the use of conventional construction and operating equipment, methods, and procedures

- Promote safety during construction activities and disposal operations
- Permit the monitoring and collection of any water that may accumulate in the disposal units during the operations, closure and institutional control periods.

Design Considerations for Concrete Structures. Where reinforced concrete structures are used for GTCC LLW disposal, the structures will be designed to satisfy the requirements stated in ACI 349-90. Additionally, the structure must be watertight by limiting the stresses and controlling cracking in accordance with ACI 350R-89.

The thickness of the structural elements and the elements providing reinforcement in the concrete sections should be designed using two approaches if those elements will be exposed to the weather or earth. First, to prevent potential cracking of the concrete, the normal tensile strength of the plain concrete section will be greater than all tensile stresses in the structural elements. Second, if it is assumed that the concrete bears no tension force (i.e. the reinforcement elements carry all tension force) the calculated probable maximum crack width in the concrete should be less than the general guide for tolerable crack width for typical exposure conditions given in ACI 224R-89. The guidance for durable construction under ACI 201,2R-82 must also be considered in the design.

Loading Combination. A 500-year credible earthquake is used as the design basis earthquake. On the basis of modified ACI 349-90, the required strength of the reinforced concrete structures or structural elements, U, is at least equal to the greatest of the following:

$$
\begin{aligned}
U1 &= 1.4D + 1.4F + 1.7H + 1.7E \\
U2 &= 1.4D + 1.4F + 1.7L + 1.7W \\
U3 &= D + L + T + E + H \\
U4 &= D + L + T + W + H \qquad (4\text{-}1)
\end{aligned}
$$

where

D = dead loads, or related moments and forces

L = live loads, or related moments and forces

F = loads resulting from lateral and vertical pressure of incidental liquid, or related moments and forces, if applicable

H	=	loads resulting from earth pressure, or related moments and forces, where applicable
T	=	loads from temperature differences within the structure, or related moments and forces
W	=	loads from design wind pressure, or related moments and forces
E	=	loads generated by the design basis earthquake, or related moments and forces.

Material Properties. Properties required of concrete and reinforcing steel for waste disposal structures such as vaults and modular concrete canisters include:

Portland cement	Type II
Specified compressive strength of concrete (psi)	5.0E+03
Reinforced concrete density (g/cm3)	2.40
Average waste/grout density (g/cm3)	1.92
Concrete porosity	0.21
Average waste/grout porosity	0.30
Minimum cement content in concrete (kg/m3)	360.
Initial pH for concrete	12.5
Minimum concrete cover over reinforcement (in):	
Exterior faces of vaults and canisters	2.5
Interior faces of vaults and canisters	2.0
Poisson's ratio for concrete	0.15 - 0.2
Maximum water-cement ratio for concrete	0.4
Maximum concrete permeability (cm/sec)	2.0E-11
Concrete Constituent Concentrations (mole/L):	
Calcium concentration in C-S-H system	1.75
Calcium concentration in Pore Fluid	2.0E-02
CaO content in cement	2.11
Silica concentration in C-S-H system	0.71
Initial chloride concentration in concrete	5.0E-03
Maximum diffusion coefficient in concrete (cm2/sec):	
Ca (OH2), NaOH, KOH	1.0E-6
Cl-	1.0E-7
SO4++	1.0E-7
O2, CO2	1.0E-6
Ca(OH)2	1.0E-6

Constituent Solubilities (mole/L):	
$Ca(OH)_2$	2.0E-02
CO_3^{--}, Mg^{++}	1.2E-03
Specified yield strength of reinforcement (psi)	6.0E+04
Specified compressive strength of grout (psi)	2.0E+03
Average air content of concrete (percent)	5 to 6

Epoxy-coated reinforcement will be used and will conform to ASTM A775 and ASTM D3963/D3963M-87. The aggregates must be shown by records or laboratory examination to minimize the potential for alkali-silica reaction, cement-aggregate reaction, or expansive alkali-carbonate reaction. The maximum sulfate, sulfide, or chloride content in aggregate and sand or concrete must be less than 0.05% by weight of cement. The maximum silt, clay, or dust content of the aggregate must be less than 0.5% by weight of aggregate. The concrete must be capable of withstanding at least 300 freeze/thaw cycles in accordance with ASTM C666, ASTM C671, and ASTM C682. Air-entrained admixtures must conform to ASTM C260. The backfill material which will contact the canisters must be controlled to minimize the chemical attack of reinforced concrete.

Allowable Maximum Stress. The canister is designed to be watertight. Design requirements for allowable concrete and steel stresses for structural elements at service loads are presented in ACI 350R-89. The service load stresses must not exceed the following:

Concrete in flexure compression (psi)	$0.45\ fc'$
Concrete in direct tension (psi)	$0.1\ fc'$
Shear stress carried by concrete (psi)	$1.1\ (fc')^{0.5}$
Bearing on loaded area (psi)	$0.3\ fc'$
Reinforcing steel in flexural tension (psi)	$0.4\ fy$
Reinforcing steel in direct tension (psi)	14,000

where

fc' = specified compressive strength of concrete (psi)

fy = specified yield strength of reinforcement (psi).

Cracking Control. Design for controlling cracking in flexural elements and tensile elements must follow guidance contained in ACI 224R-89 and ACI 350R-89. The maximum tolerable crack width at the tensile face of the reinforced concrete structures under typical conditions is:

Index of crack control (Z), limiting distribution of reinforcement	
Normal exposure condition (kip/in.)	115
Severe exposure condition (kip/in.)	95
Maximum crack width exposed to	
Dry air or protective membrane (in.)	0.016
Moist air, soil environment (in.)	0.012

Allowable Roof Displacement. Allowable roof displacement over span is no greater than 1/500.

Structural Stability. Required safety factors for the stability of structure are summarized as follows:

Under normal conditions	
Resistance to overturning	2.00
Resistance to sliding	2.00
Under abnormal conditions	
Resistance to overturning	1.50
Resistance to sliding	1.50

Special Requirements for the Aboveground Vault Disposal Unit. A protective enclosure must be provided from the beginning of construction until facility closure. This protective enclosure must be freestanding and provide weather and frost protection for the disposal unit. It must also be watertight and easy to inspect and repair. The protective enclosure structure must be designed to conform with the Uniform Building Code (UBC-1991).

The aboveground vault should be carefully designed and constructed to prevent any cracks that may develop and penetrate to the disposed waste. The surfaces of the concrete structure that are exposed to the weather should be sealed and coated. The structure should be capable of being monitored for long-term performances.

Engineered Cover Systems. All potential GTCC LLW disposal concepts will be provided with an engineered cover system. The cover system helps isolate the waste from the environment and reduces the potential for contact between water and waste. The cover systems are designed to

- Minimize the potential for water to infiltrate into and percolate through the disposal unit
- Direct surface and percolating water away from the disposal unit
- Reduce exposure rates at the upper surface to levels that satisfy 10 CFR 20 requirements for occupational exposures
- Assist in the long-term isolation of the waste from the environment
- Resist degradation by surface geologic processes and biotic activity
- Prohibit water velocities or gradients that would result in erosion that would require ongoing active maintenance
- Act as a barrier to intrusion by humans, plants, and animals
- Minimize surface erosion, differential settlement, ponding, piping, sloughing, and slumping
- Minimize the potential for liquefaction.

The design criteria for the cover systems are as follows:

- At least 10 m (33 ft) of earthen cover system are required for near-surface disposal units

- At least 2 m (6.5 ft) of earthen cover system above native grade are required for the intermediate-depth or deep geologic drilled hole and mined cavity disposal concepts

- The maximum amount of percolation is determined so projected dose rates to any member of the general public via the groundwater pathway do not exceed limits specified in 10 CFR 61, Subpart C

- The minimum slope of each cover layer is 1% to ensure adequate drainage

- The maximum side slope of each cover layer is 20% to ensure stable surfaces

- The minimum drainage layer permeability is 1.0E-02 cm/s (3.9E-03 in./s) to ensure proper drainage

- The maximum in-place coefficient of permeability for clay is 1.0E-07 cm/s (3.9E-08 in./s) to ensure an adequate resistance to water flow

- The minimum clay thickness is 0.6 m (2 ft) to ensure adequate resistance to water flow.

Surface Water Management System. The surface water management system includes protective measures for the probable maximum flood event, the surface water drainage system, and the retention pond, as necessary. The drainage system for surface water is provided to protect the disposal facility from the effects of surface water run-on and to conduct surface water runoff away from the vicinity of the disposal units. The retention pond is only required for near-surface disposal facilities.

The drainage system for surface water consists of berms, grades, ditches, and drainage structures that will accomplish the following functions:

- Prevent surface water run-on from areas adjacent to the disposal facility

- Direct potentially infiltrating surface water away from disposed waste at velocities that will not cause erosion that requires ongoing active maintenance

- Resist degradation by surface geologic processes and biotic activity

- Complement and improve the ability of the site to ensure that the performance objectives are satisfied

- Provides a retention pond for near-surface disposal facilities to collect runoff to permit testing of potential contamination before release.

The surface water management system should be designed according to the following design criteria:

- The capacity of each component of the system will be determined for maximum flow under worst conditions

- The minimum ditch slopes will be sufficient to produce cleansing velocities under expected flow conditions

- The maximum ditch slopes will be based on minimizing potential for erosive forces that might degrade the functions of the surface water drainage system

- Materials will be selected with consideration of maximum water velocities to minimize the potential for water erosion

- The retention pond will be sized to retain runoff from 100-year, 24-hour storm events without discharge.

Special Requirements for Vertical Shafts and Mines. Rock bolt, steel or timber frame, shotcrete, or reinforced concrete liners may be provided to support the vertical shafts and mines. The method chosen will depend on geologic and hydrologic considerations. For the potential GTCC LLW disposal concepts, reinforced concrete liners are assumed.

Consolidation grouting is required in vertical shafts and mines. This grouting stabilizes the margin of host rock adjacent to the shaft or mine that is damaged during the construction process.

Radiological Safety. The protection of workers from undue hazards associated with radiation is required by 10 CFR 20 and 10 CFR 61. The magnitude of worker exposures is closely related to the technology employed and the operating procedures at a given facility. Potential worker exposure levels will be considered and the designs should incorporate provisions to maintain worker exposures as low as reasonably achievable.

4.3.3 General Concept Description

A general description of the GTCC LLW disposal concepts is provided below. The general layout of the various concepts is described, followed by a discussion of the design basis for the modular concrete canister, which is used in several of the concepts.

Surface Facilities Layout. Common features of the layout of the near-surface GTCC LLW disposal concepts are described in this section. The site includes support facilities required for the proper conduct of the disposal operations, a disposal area where the disposal operations are performed, a buffer zone, and utilities.

Support Facilities. Common support facilities are provided for all of the GTCC LLW disposal concepts. The facilities are located in a restricted area and include an access control point (guard house), a waste inspection station, a pump house, an administration/operations support building, an equipment maintenance area, a washdown area for decontamination of trucks and other equipment, a waste storage building, a concrete batch plant (where applicable), and a materials storage area. The administration/operations support building contains offices, conference rooms, laboratories, lockers, and personnel facilities.

A retention pond is constructed for all near-surface disposal concepts. A compressed-air and water-supply building is constructed for the intermediate-depth and deep geologic disposal concepts; ventilation systems and groundwater holding tanks are included in the mined cavity concept.

Disposal Area. The disposal area is a restricted area surrounded by a chain link fence topped with barbed wire. Access to the disposal area is restricted to authorized personnel. The components of the disposal area include

- Disposal units for GTCC LLW and any waste that may result from decommissioning the facility

- Surface water drainage system
- Retention ponds for the near-surface disposal concepts
- A compressed-air and water-supply building for the drilled hole and mined cavity concepts
- A waste-handling and ventilation building or ventilation system for the mined cavity concept
- Onsite service roads and perimeter roads
- Stockpile area
- Onsite monitoring system.

The general support area is a portion of disposal area adjacent to the administration area. The buildings and facilities located in this area include

- A waste receipt and storage building
- A decontamination facility
- An equipment storage and maintenance building
- A concrete batch plant for grouting modular concrete canisters.

Buffer Zone. A 100-m (300-ft) buffer zone is provided between unrestricted land areas and the disposal area on three sides of all GTCC LLW disposal facility, the buffer zone in the administrative area is 61 m (200 ft) wide. Access to the buffer zone is controlled from both sides by chain link fences. A guard station is located at the outer perimeter to limit entry to authorized personnel and to control potential exposures to radiation. Facilities located in the buffer zone include

- Environmental monitoring installations and equipment

- A guard house
- Parking areas
- An administrative/operations support building (including health physics, security, laboratory, and change room)
- A pumphouse and water-storage tank
- Access roads
- A drainage system (water incident on buffer zone will be diverted away from disposal area)
- Fencing and gates.

In addition to the buffer zone described above, a minimum of 100 m (300 ft) will be maintained between the disposal area and the inner fence or between the disposal area and the boundary of the general support area.

Utilities. Utilities required for operation of the disposal site are those common to most industrial operations. They include electricity, water, telephone service, and sanitary sewers connected to a septic tank (because of the remoteness of the site). Storage tanks for gasoline and diesel fuel needed to operate site vehicles and equipment will also be located onsite. As stated earlier, a compressed-air and water-supply building is constructed for the intermediate-depth and deep geologic facilities; ventilation systems and groundwater holding tanks are included in the mined cavity disposal facilities.

Modular Concrete Canister Design Basis. Modular concrete canisters are used in one of the near-surface disposal concepts and all of the intermediate-depth and deep geologic concepts. Several different configurations of the canisters could be considered for use because of the variety of high-integrity and high-level-waste type containers that may be used for GTCC LLW disposal. For the technical evaluation of the GTCC LLW disposal concepts, a single modular concrete canister design was selected that would accommodate several different waste packages.

Selection of the modular concrete canister design was based, in part, upon limiting occupational exposures to fewer than 100 mrem/hr from the unshielded canister. A portion of the waste, comprising roughly 10% of the total GTCC LLW volume, required canisters with much thicker walls in order to achieve this goal. Use of these canisters for all GTCC LLW would require special handling equipment and would nearly double the disposal capacity required for the waste. To circumvent the need for the more robust canisters, the design of the mined cavity concept was modified to permit remote handling of the highest activity waste. Special design features were not required for the near-surface or drilled hole disposal concepts.

The modular concrete canister design selected for use in the technical evaluation accommodates four sizes of high-integrity containers and the high-level-waste type containers. The canister has an exterior diameter of 2.6 m (8.7 ft) and is 2.8 m (9.25 ft) tall (Figure 4-1). The outer rim of the top of the canister has a 5-cm (2-in.) rim which may be used for lifting. The interior dimensions of the canister are 2.0 m (6.7 ft) in diameter and 2.1 m (6.9 ft) in height. A summary of dimensions and physical characteristics of the canister is provided in Table 4-8.

The modular concrete canister is assumed to be capable of withstanding all loads placed on it, based on the working conditions and ACI codes that were applied in the design process, including ACI 349-90, 224R-89, 350R-89, 201.2R-77 (Reaffirmed 1982). The steel reinforcement design in the canister is based on engineering judgement. More detailed justification will be required for the preliminary design of the canister.

4.3.4 GTCC LLW Disposal Concept Conceptual Designs

The conceptual designs of the GTCC LLW disposal concepts are provided below. The near-surface disposal concepts are discussed first, followed by descriptions of the intermediate-depth and deep geologic concepts.

Near-Surface Disposal Concepts. The near-surface GTCC LLW concepts include shallow-land disposal, modular concrete canister, belowground vault, earth-mounded vault, and aboveground vault facilities. Features common to these concepts are discussed here, specific design characteristics of each concept are provided in the following paragraphs.

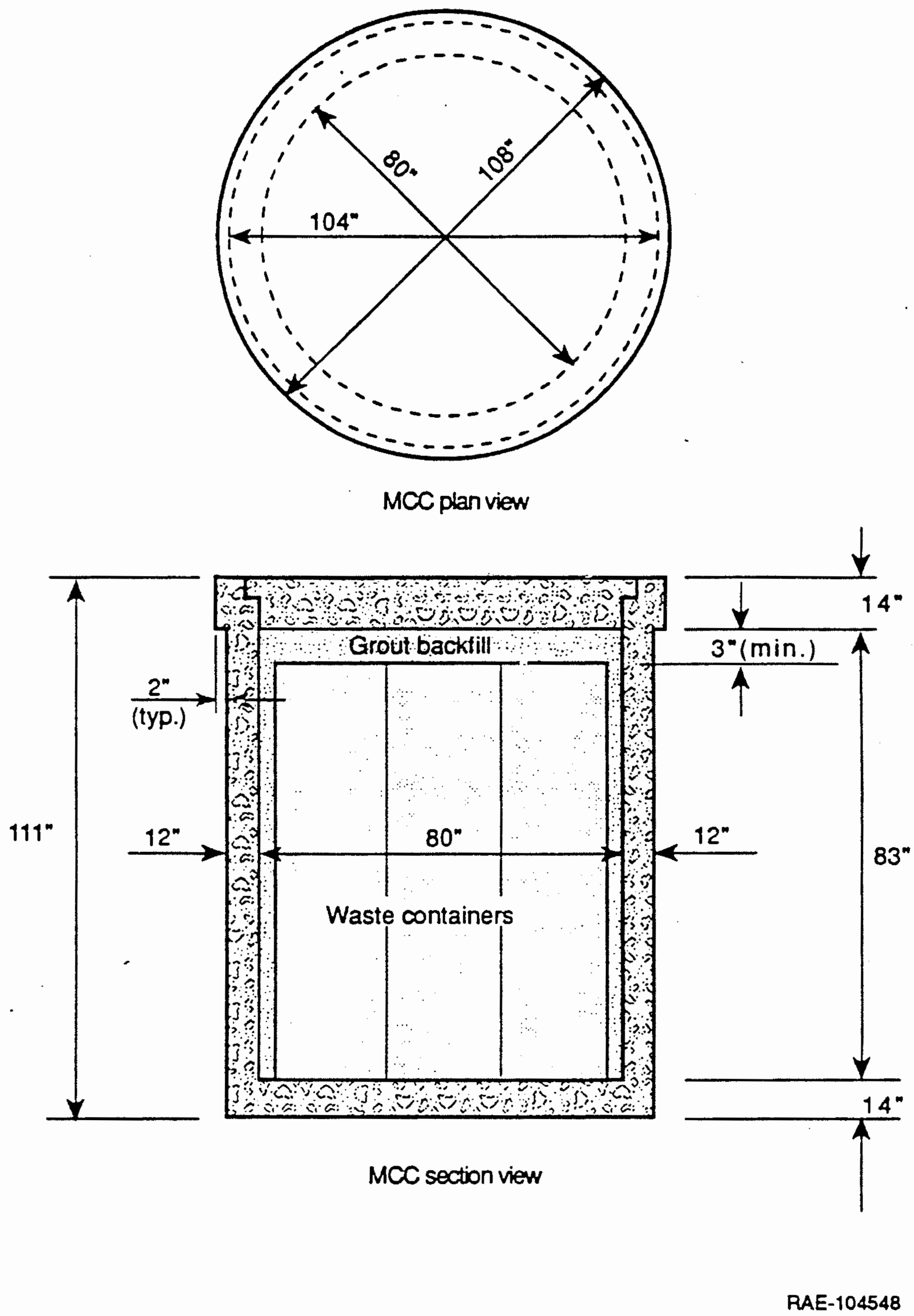


Figure 4-1. Dimensional detail of modular concrete canister.

Table 4-8. Physical characteristics and reinforcements in the modular concrete canister.

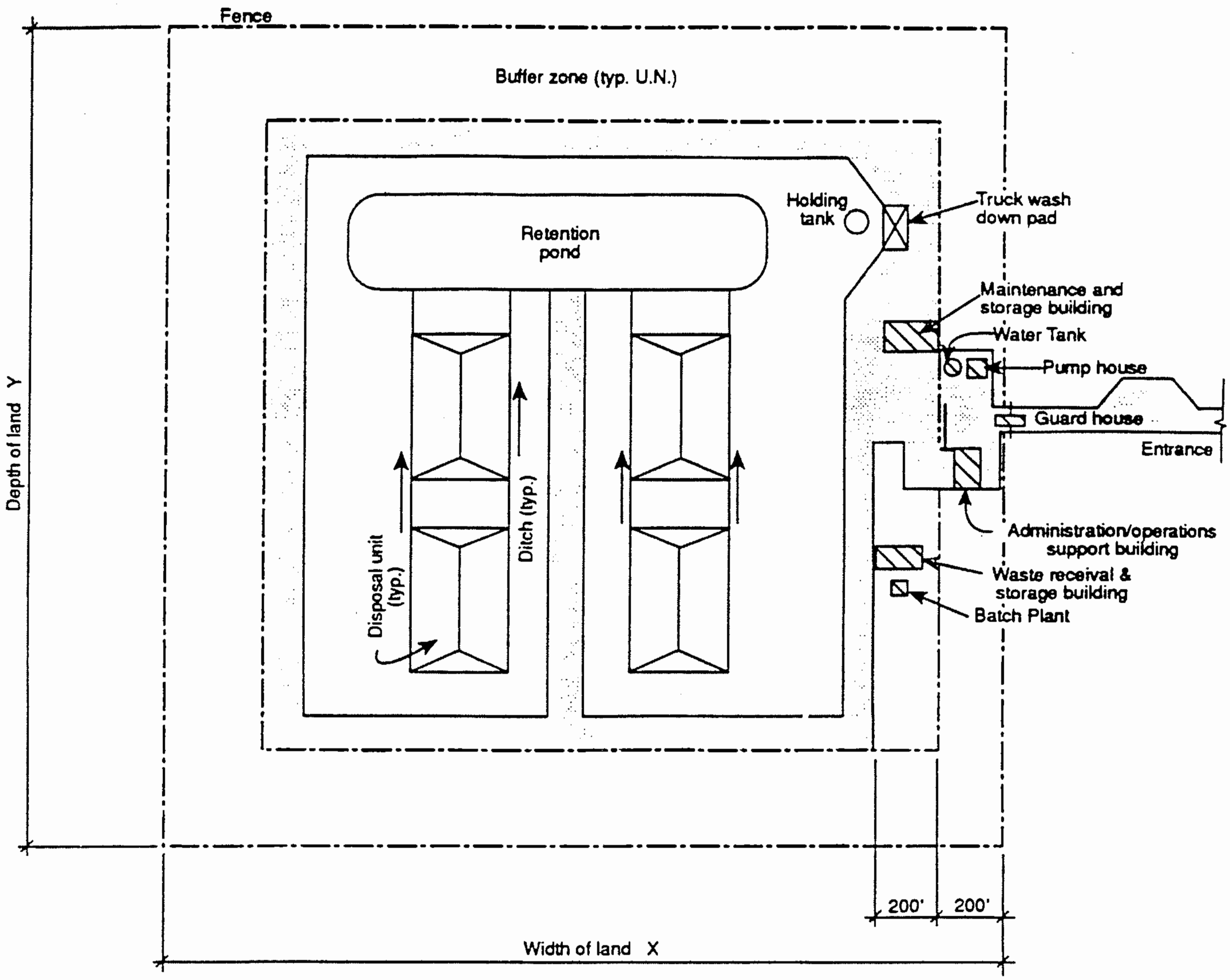
Cylindrical shell of wall:	
Wall thickness (in.)	12
Inside diameter (in.)	80
Inside height (in.)	83
Nominal outside diameter (in.)	104
Outside height (in.)	111
Circular roof thickness (in.)	14
Circular floor thickness (in.)	14
Specified compression strength of concrete at 28 day (psi)	5,000
Steel reinforcement size and space in canister elements	
Wall - exterior face, vertical	#5 @ 6" o.c.
Wall - interior face, vertical	# 5 @ 6" o.c.
Wall - exterior face, ring	#5 @ 6" o.c.
Wall - interior face, ring	#5 @ 6" o.c.
Roof - exterior face, both ways	#5 @ 6" o.c.
Roof - interior face, both ways	#5 @ 6" o.c.
Floor - exterior face, both ways	#5 @ 4" o.c.
Floor - exterior face, both ways	#5 @ 4" o.c.

All of the near-surface GTCC LLW disposal concepts have a layout similar to that shown in Figure 4-2. Each of the concepts includes support facilities for administration, operations, access control, maintenance, decontamination, and waste receiving/storage, as discussed in Section 4.3.3. The specific dimensions of these facilities and the land requirements differ between disposal concepts. These differences are discussed below.

With the exception of the aboveground vault concept, each of the near-surface concepts will utilize engineered cover systems, shown in Figure 4-3. An interim cover will be used prior to installation of the final engineered cover system. The final cover will consist of (in ascending order)

- A 15.2-cm (6-in.) layer of gravelly sand
- A 0.9-m (3-ft) layer of compacted bentonite clay
- A 7.8-m (25.5-ft) layer of native soil
- A layer of geotextile
- A 0.6-m layer of gravel/cobble, which serves as a subsurface drainage layer and biobarrier
- A 15.2-cm (6-in.) layer of pea gravel
- A 15.2-cm (6-in.) layer of sand
- A 0.3-m (1-ft) layer of topsoil seeded with native vegetation.

Shallow-Land Disposal Concept. The shallow-land disposal concept is shown in Figures 4-4 and 4-5. Each of the four disposal units consists of a sloped trench, which, when open, will measure approximately 95 m (313 ft) long by 57 m (188 ft) wide and will be excavated to a depth of approximately 16 m (52 ft). The actual waste emplacement area at the bottom of the trench will measure 6.4 by 44 m (21 by 146 ft). The bottom of the trench will be covered with a minimum of 0.6 m (2 ft) of sandy gravel and 15.2 cm (6 in.) of pea gravel. A subgrade drainage layer and a french drain are installed in one side of the trench; a monitoring well will extend to the ground surface from the french drain.



Land requirements for the near-surface facilities				
Disposal concept	Width of land X (ft.)	Depth of land Y (ft.)	Total site area (ac.)	Waste disposal area (ac.)
Shallow-land disposal	1380	1930	61	27
Belowground modular concrete canister	1380	2870	91	46
Belowground vault	1410	2230	72	34
Earth-mounded concrete vault	2090	3100	149	91
Aboveground vault	1120	1870	48	18

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Figure 4-2. Near-surface disposal concept layout plan.

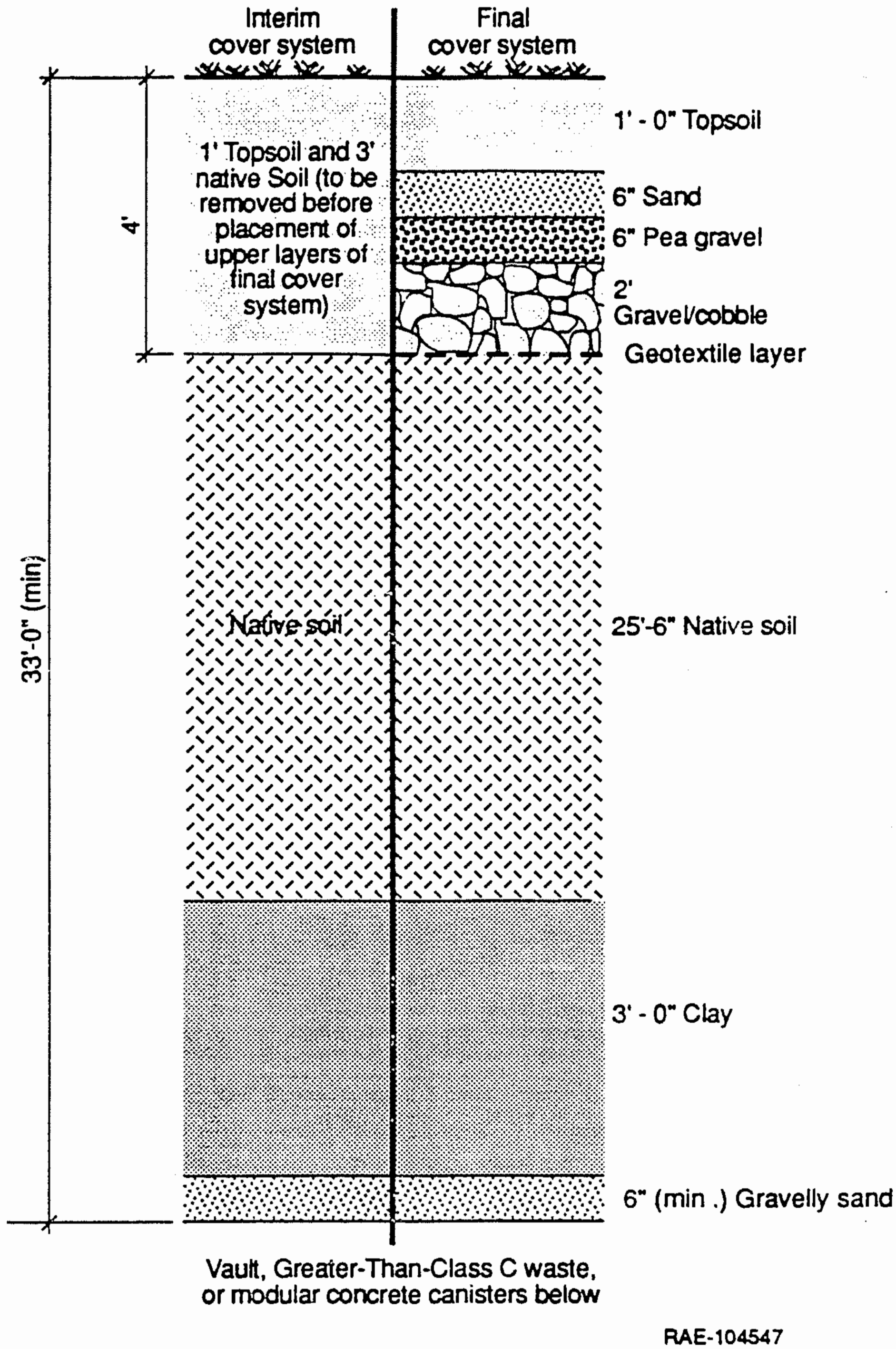

Figure 4-3. Near-surface disposal unit cover systems.

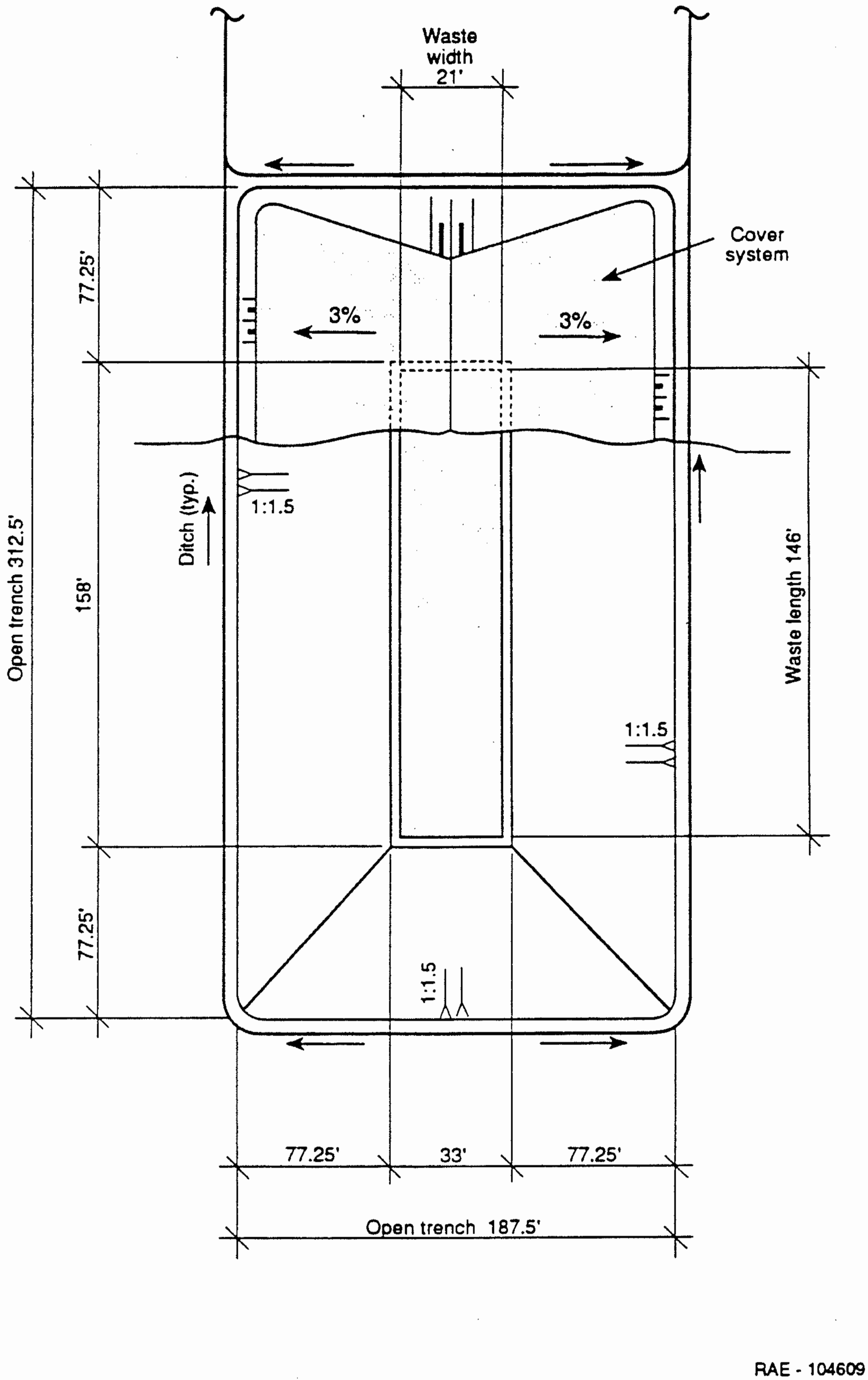

Figure 4-4. Shallow-land disposal unit plan.

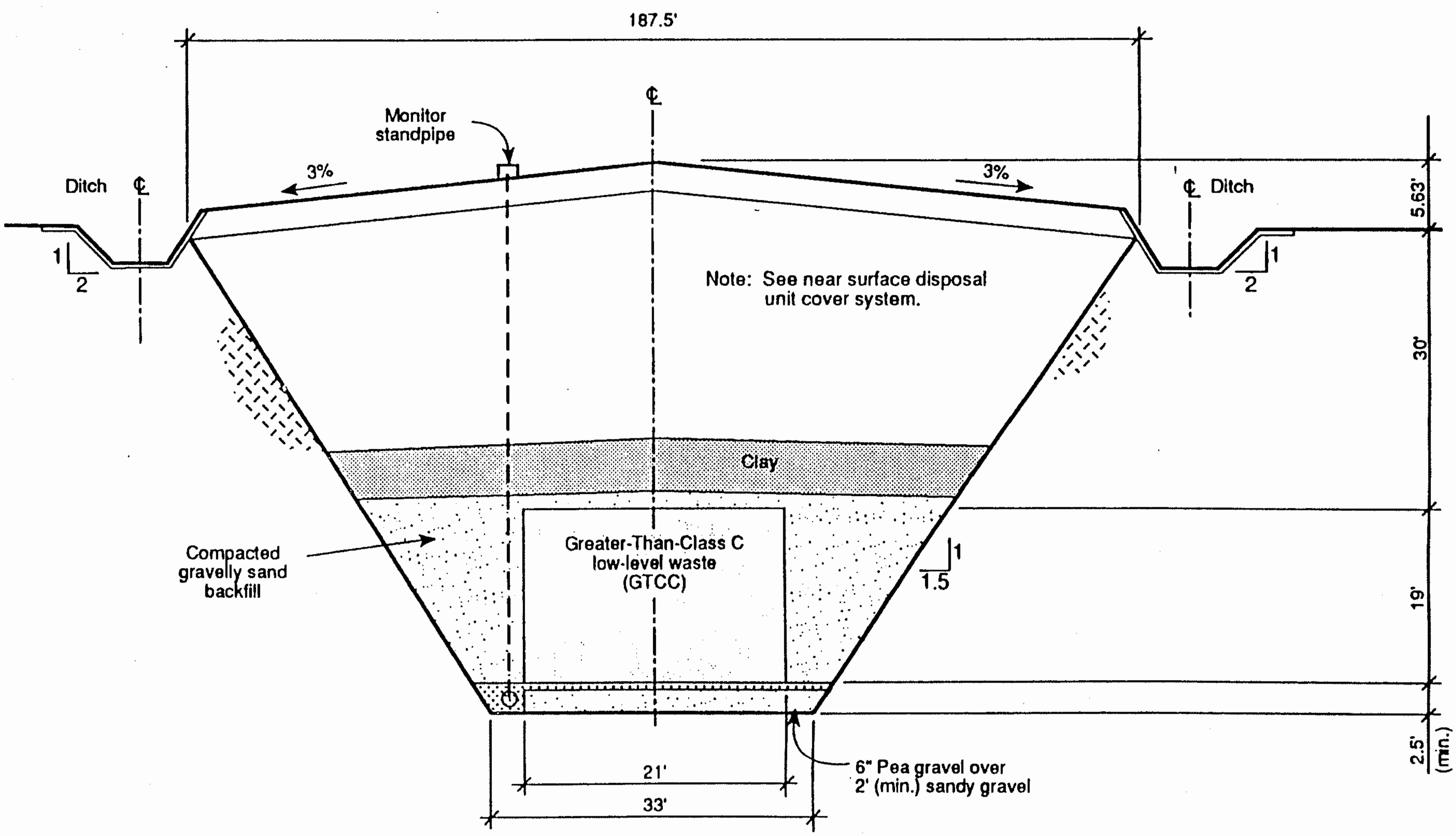

Figure 4-5. Cross section of shallow-land disposal unit.

Waste packaged in high-integrity containers is placed in the trench using a boom crane or forklift. The waste will be placed in a layered configuration on top of the pea gravel to a height of approximately 5.8 m (19 ft). Void spaces around, between, and above the containers will be filled with compacted gravelly sand. The layer of gravelly sand on top of the waste represents the bottom-most layer of the engineered cover system. A summary of disposal site, disposal area, and disposal unit characteristics for the shallow-land disposal concept is provided in Table 4-9.

Modular Concrete Canister Disposal Concept. The modular concrete canister disposal concept (Figures 4-6 and 4-7) is similar to the shallow-land disposal concept in that there are 4 disposal units, each of which consists of a sloped trench. The open disposal units will measure approximately 23.2 m (760 ft) long by 58 m (189 ft) wide and will be excavated to a depth of about 16 m (52 ft) below grade. The actual waste emplacement area at the bottom of each trench will measure 8.1 m (26.5 ft) by 184 m (605 ft). The bottom of the trenches will be covered with a minimum of 0.6 m (2 ft) of sandy gravel and 15.2 cm (6 in.) of pea gravel. A french drain is installed in one side of each trench, a monitoring well will extend up to the ground surface from the french drain.

Waste will be packaged in high-integrity containers, loaded into the concrete canisters, and grouted. The filled canisters will be placed in the trench using a boom crane or forklift. The canisters will be placed in a two-layer configuration to a height of approximately 5.8 m (19 ft). Void spaces between canisters will be filled with pea gravel, and gravelly sand will be placed around and above the placed canisters. The layer of gravelly sand on top of the canisters represents the bottom-most layer of the engineered cover system. A summary of disposal site, disposal area, and disposal unit characteristics for the modular concrete canister disposal concept is provided in Table 4-10.

Belowground Vault Disposal Concept. The belowground vault disposal concept consists of a reinforced concrete vault constructed in an excavated trench (Figures 4-8 and 4-9). There are 4 disposal units, each consisting of a sloped trench, which, when open, will measure approximately 138 m (454 ft) in length 65 m (212 ft) in width and will extend to a depth of 18 m (58 ft) below grade. The bottom of each trench will be covered with a minimum of 0.6 m (2 ft) of sandy gravel and 15.2 cm (6 in.) of pea gravel. A french drain is installed in one side of the trench, and a monitoring well extends from the drain to the ground surface.

Each vault consists of 11 disposal cells, a thermal expansion joint is provided between groups of two or three disposal cells. The vaults will be 8.7 m (28.5 ft) wide, 82 m long (270.5 ft), and 7.9 m

Table 4-9. Summary of disposal site and disposal unit physical characteristics for the shallow-land disposal concept.

Characteristic	Value
Site dimensions (ft x ft)	1380 x 1930
Total site area (ac)	61
Disposal area dimensions (ft x ft)	880 x 1330
Total disposal area (ac)	27
GTCC LLW Disposal Unit	
Number of units	4
Trench base dimensions (ft x ft)	158 x 33
Trench top dimensions (ft x ft)	312.5 x 187.5
Height of waste in unit (ft)	19
Unit disposal capacity (ft^3)	28,750
Minimum thickness of soil cover (ft)	33

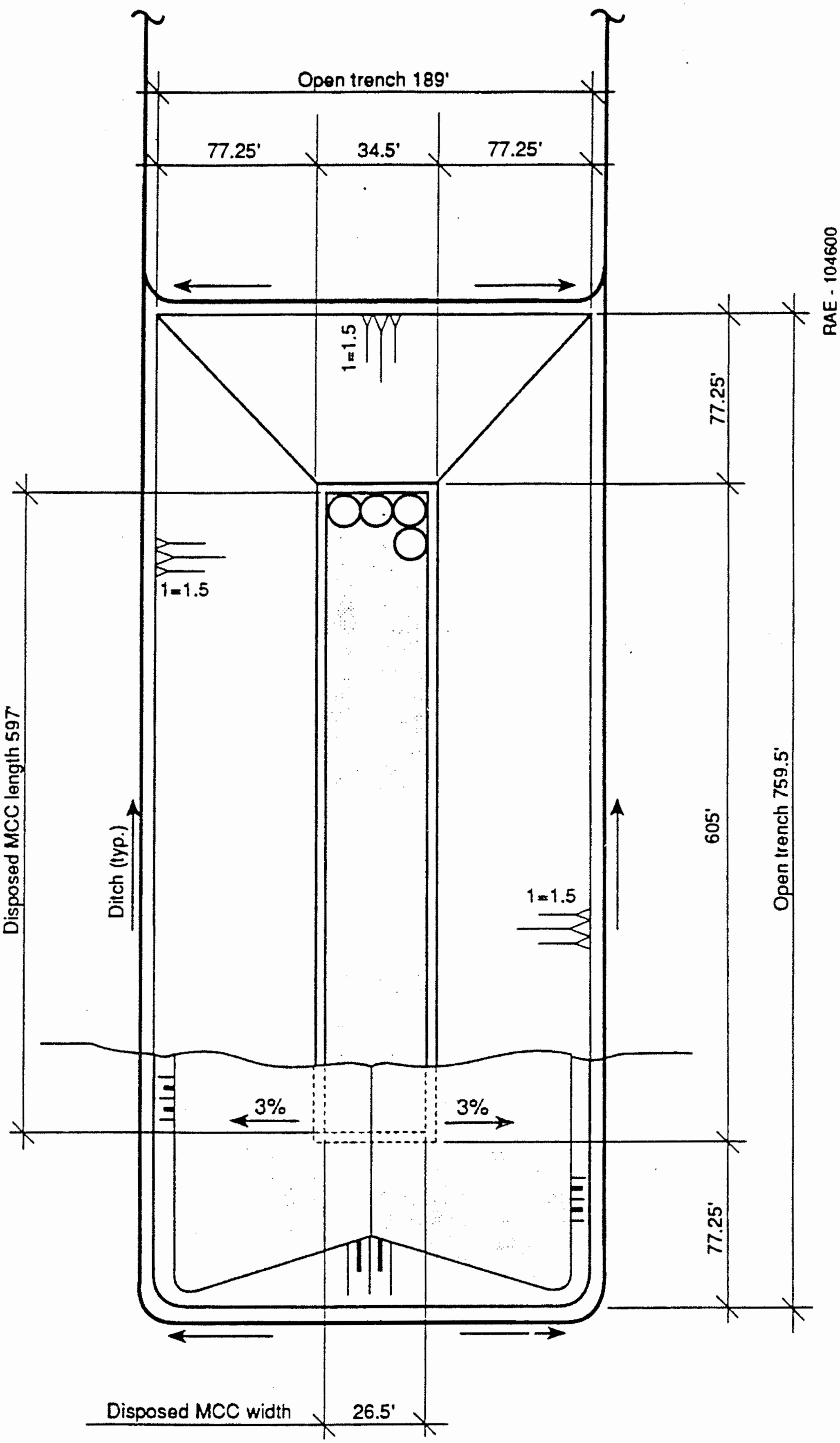

Figure 4-6. Modular concrete canister disposal unit plan.

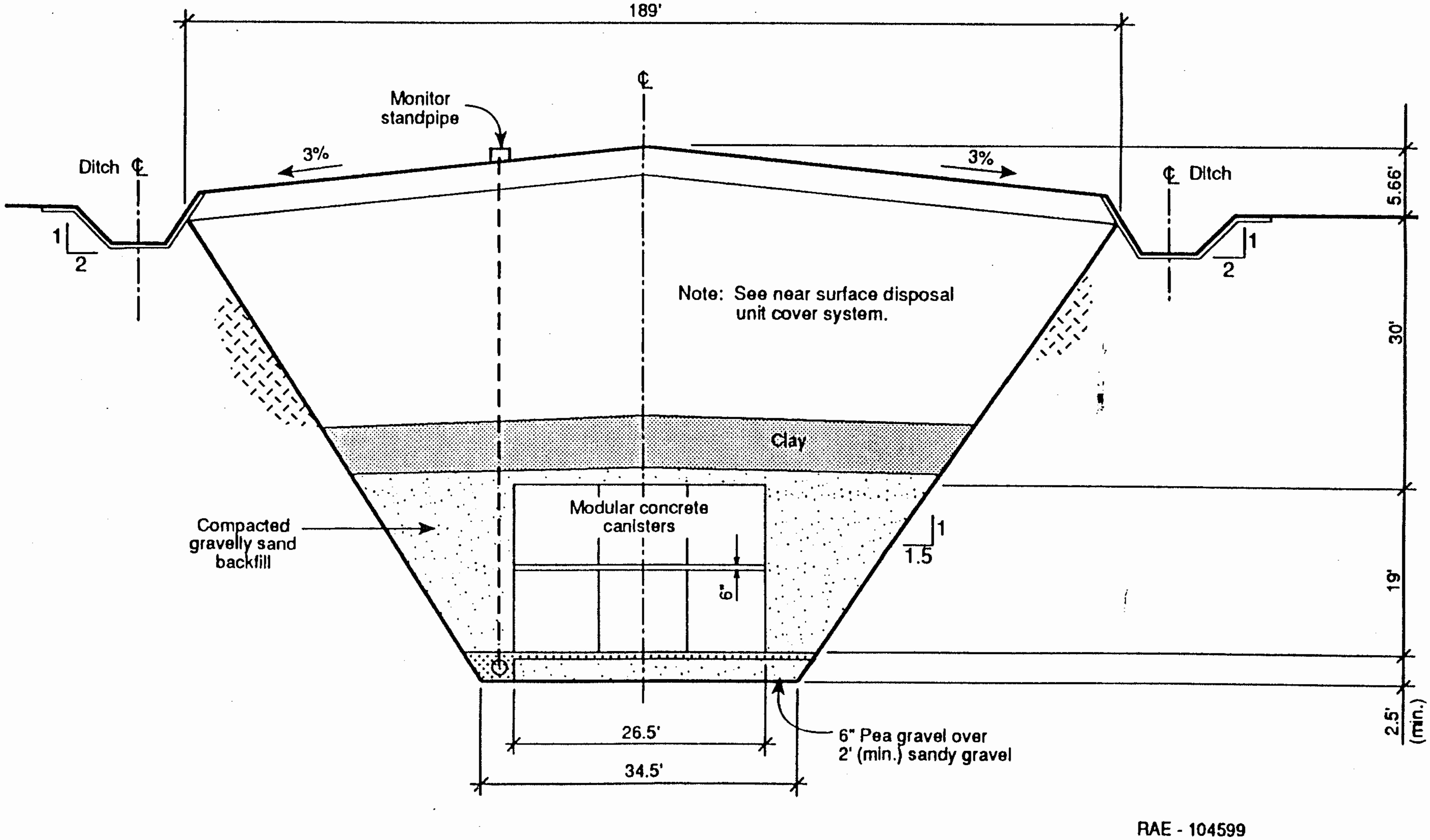

Figure 4-7. Cross section of modular concrete canister disposal unit.

Table 4-10. Summary of disposal site and disposal unit physical characteristics for the modular concrete canister disposal concept.

Characteristic	Value
Site dimensions (ft x ft)	1380 x 2870
Total site area (ac)	91
Disposal area dimensions (ft x ft)	880 x 2270
Total disposal area (ac)	46
GTCC low-level waste disposal unit	
Number of units	4
Trench base dimensions (ft x ft)	605 x 34.5
Trench top dimensions (ft x ft)	759.5 x 189
Minimum open trench depth (ft)	
Canister number in rows (ea)	3
Canister number in rank (ea)	67
Canister layer in height (ea)	2
Backfill layer between canisters (in.)	6
Stacked canister height in disposal unit (ft)	19
Total number of MCC in disposal unit (ea)	400
Unit disposal capacity (ft^3)	28,750
Minimum thickness of soil cover (ft)	33

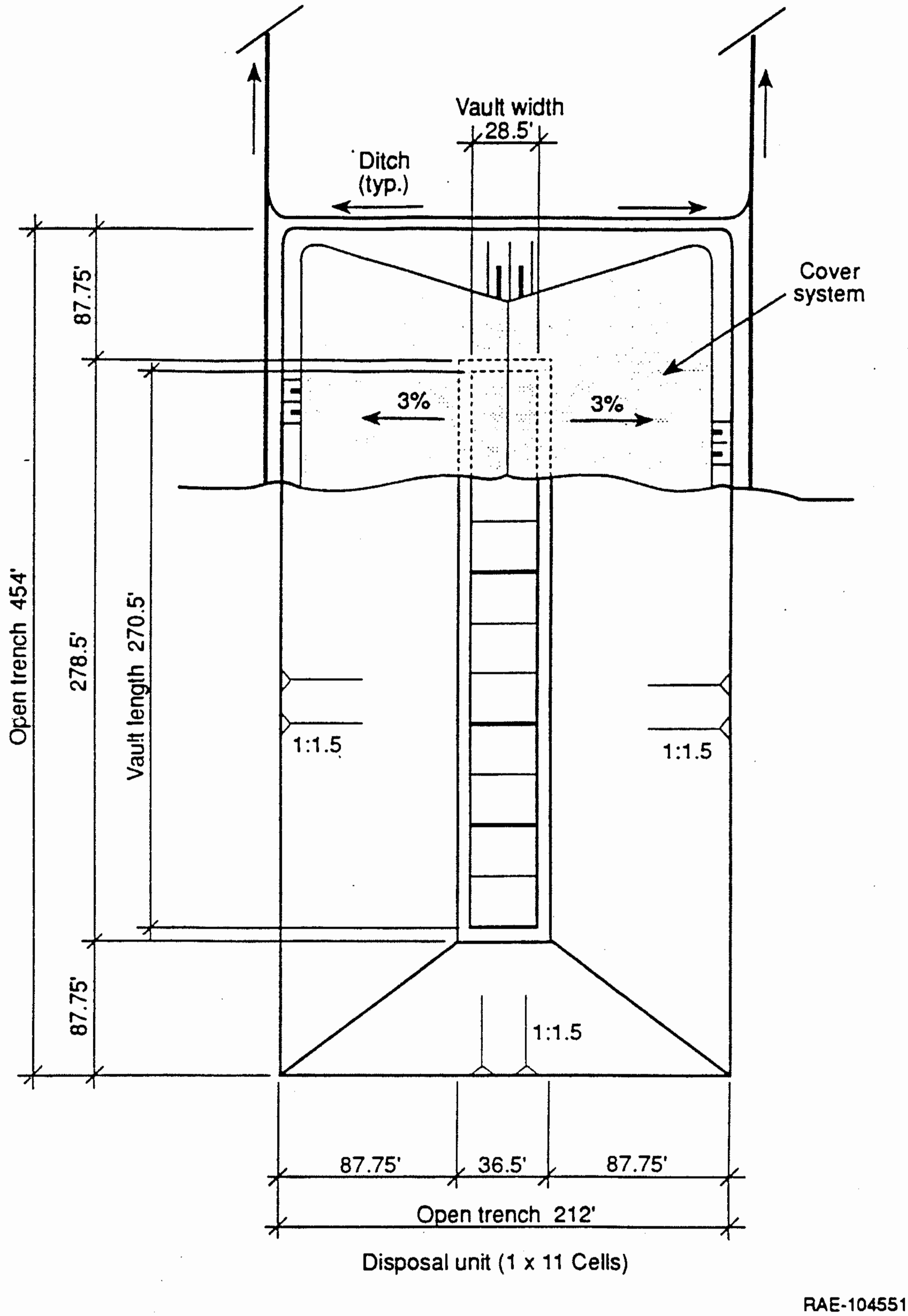

Figure 4-8. Belowground vault disposal unit plan.

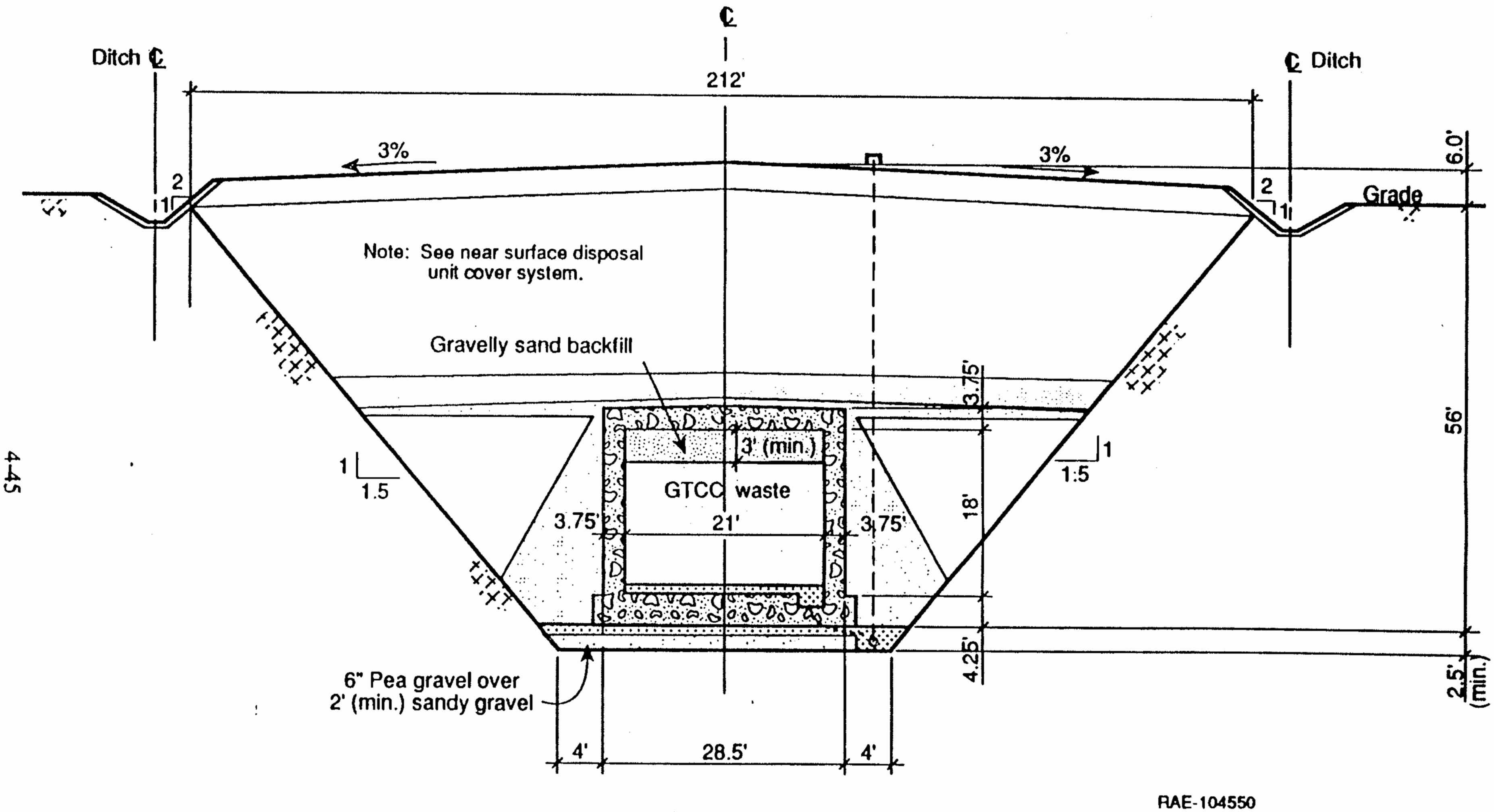

Figure 4-9. Cross section of belowground vault.

(26 ft) tall. The floor of vault is constructed with 0.6 m (2 ft) overhangs on all exterior faces of the structure. Each disposal cell is 6.4 m (21 ft) wide, 6.4 m (21 ft) long, and 5.5 m (18 ft) high. A 15.2-cm (6-in.) gravelly drainage layer will be placed on the floor of the disposal cells.

Waste packaged in high-integrity containers is placed in the disposal cells using an overhead or boom crane. Waste is placed in a two-layer configuration, with 0.9 m (3 ft) of gravelly sand placed between successive layers. Void spaces around and between the containers will be filled with pea gravel. Following placement of the second layer of waste, 0.9 m (3 ft) of gravelly sand is placed over the waste. Following closure of the vaults, additional gravelly sand backfill will be placed upon and around the vault. The gravelly sand placed on the vault represents the bottom-most layer of the engineered cover system. A summary of disposal facility and disposal unit characteristics for the belowground vault disposal concept is provided in Table 4-11.

Earth-Mounded Vault Disposal Concept. The earth-mounded vault disposal concept, shown in Figures 4-10 and 4-11, is identical to the belowground vault concept save for the fact that the vaults will be constructed at essentially grade level (the reader is referred to the description of the belowground vault concept). The vault will sit below the frost-line on top of a 0.6-m (2-ft) layer of sandy gravel and 15.2 cm (6 in.) of pea gravel. A summary of disposal facility and disposal unit characteristics for the Earth Mounded Vault disposal concept is provided in Table 4-12.

Aboveground Vault Disposal. The aboveground vault disposal concept is similar to the earth-mounded vault concept, save for the fact that no earthen cover system will be provided for the former (Figures 4-12 and 4-13). The vault is constructed at essentially grade level. Only a slight excavation is needed for the footings and the floors of the vaults, which must sit below frost line.

Each of the four vaults consists of 11 disposal cells. An expansion joint is provided between groups of two to three cells to permit thermal expansion without structural damage. The vaults will be 8.2 m (27 ft) wide, 82 m (269 ft) long, and 7.3 m (24 ft) tall. The vaults will be placed in a drainage layer, and a french drain will be installed in one side of the trench. A monitoring well will extend to the ground surface from the french drain.

Waste packaged in high-integrity containers will be placed in the disposal vaults using an overhead crane. Waste packages will be placed to a height of 4.6 m (15 ft), void spaces between the containers will be filled with pea gravel. A 0.9 m (3 ft) layer of compacted gravelly sand will be placed on top of the

Table 4-11. Summary of disposal site and disposal unit characteristics for the belowground vault disposal concept.

Characteristic	Value
Overall site dimensions (ft x ft)	1410 x 2230
Total site area (ac)	72
Disposal area dimensions (ft x ft)	910 x 1630
Total disposal area (ac)	34
Number of disposal units or vaults (ea)	4
GTCC LLW disposal unit	
Number of cells per vault (ea)	11
Interior cell dimensions (L x W x H, ft)	21 x 21 x 18
Exterior vault dimensions (L x W x H, ft)	270.5 x 28.5 x 26([a])
Minimum backfill thickness on top of waste inside cell (ft)	3
Roof thickness (in.)	45
Exterior wall thickness (in.)	45
Interior wall thickness (in.)	24
End wall thickness (in.)	30
Floor thickness (in.)	51
Specified compression strength of concrete at 28 days (psi)	5,000
Specified yield strength of reinforcement (psi)	60,000
Reinforcement size and space in the vault elements:	
Roof - exterior face, both ways	#7 @ 6" o.c.
Roof - interior face, both ways	#9 @ 6" o.c.
Exterior wall - exterior face, both ways	#8 @ 6" o.c.
Exterior wall - interior face, both ways	#7 @ 6" o.c.
Interior wall - both face, both ways	#6 @ 6" o.c.
End wall - exterior face, both ways	#7 @ 6" o.c.
End wall - interior face, both ways	#7 @ 6" o.c.
Floor - exterior face, both ways	#8 @ 6" o.c.
Floor - interior face, both ways	#10 @ 6" o.c.
Minimum trench excavation depth (ft)	
Trench excavation at grade (L x W, ft)	485 x 152.5
Trench excavation at base (L x W, ft)	
Overall waste placement efficiency in cell (percent)	41[b]
Minimum earthen cover thickness (ft)	33

a. Ignoring 2 feet floor overhang from faces of exterior walls.

b. Depending on waste container.

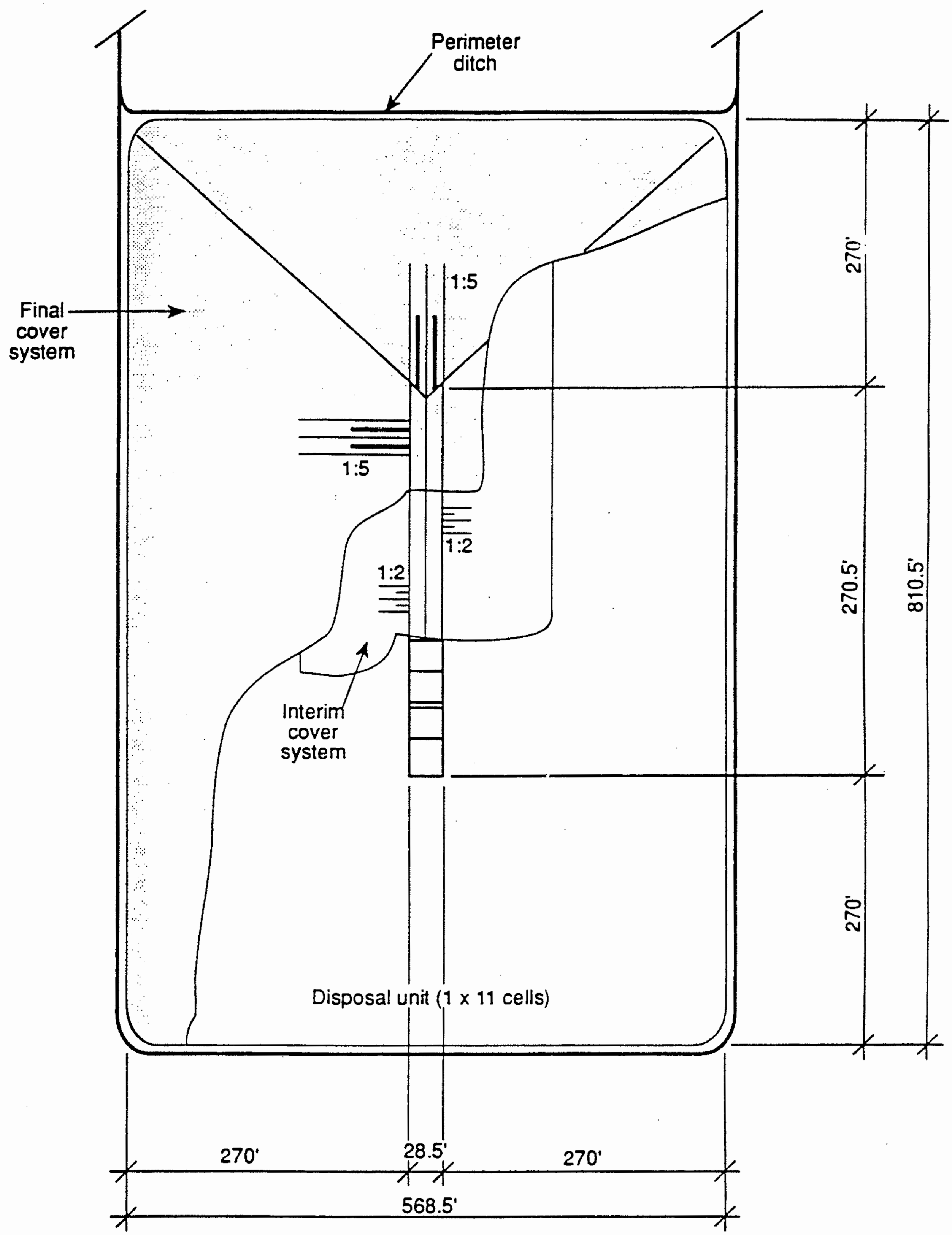

Figure 4-10. Earth-mounded vault disposal unit plan.

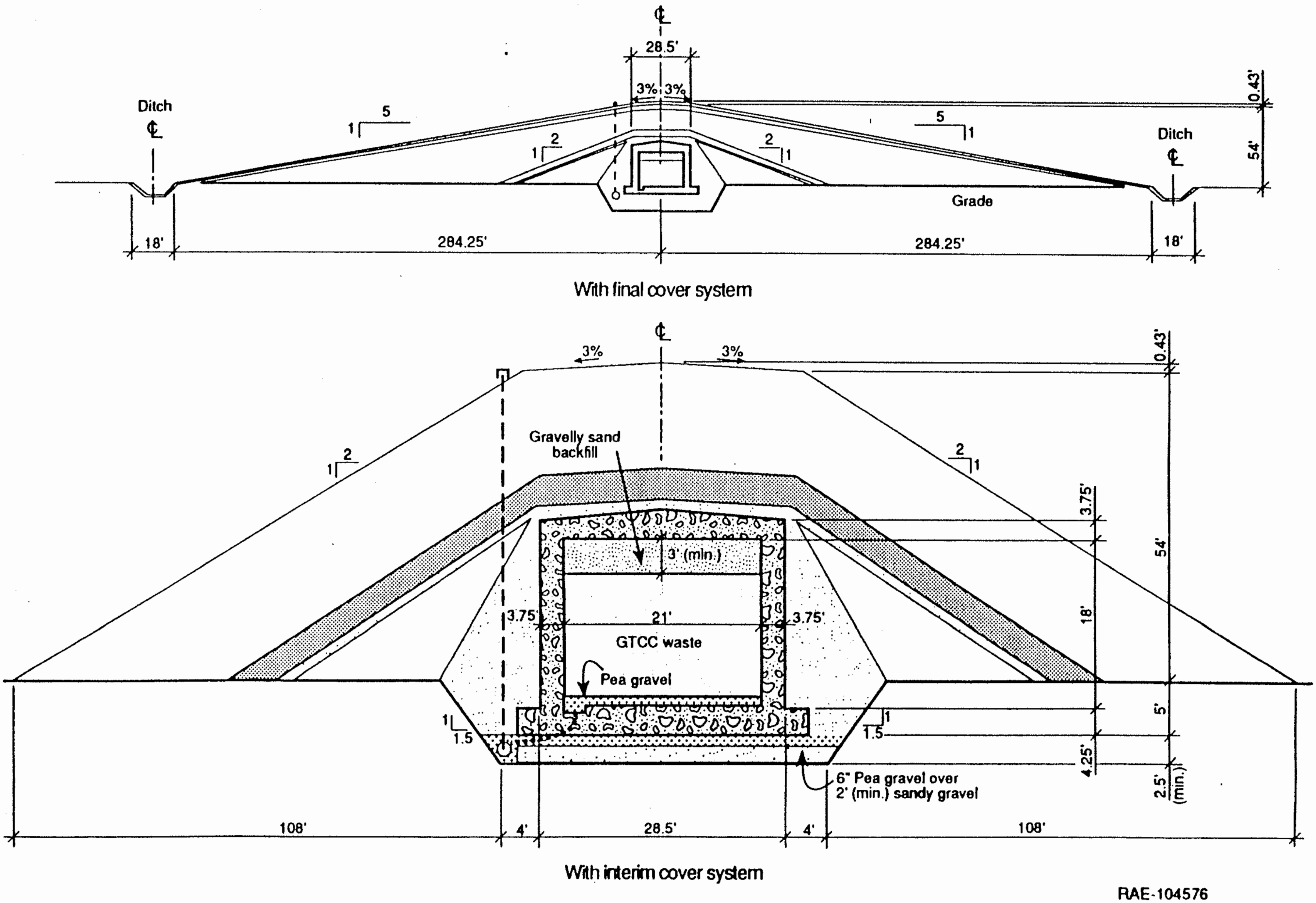

Figure 4-11. Cross sections of earth-mounded vault disposal unit.

Table 4-12. Summary of disposal site and disposal unit physical characteristics for the earth-mounded vault disposal concept.

Characteristic	Value
Overall site dimensions (ft x ft)	2090 x 3100
Total site area (ac)	149
Disposal area dimensions (ft x ft)	1590 x 2500
Total disposal area (ac)	91
Number of earth-mounded units (ea)	4
Earthmound disposal unit	
Number of vaults in earth-mounded unit (ea)	1
Number of cells per vault (ea)	11
Interior cell dimensions (L x W x H, ft)	21 x 21 x 18
Exterior vault dimensions (L x W x H, ft)	270.5 x 28.5 x 26[a]
Backfill thickness on top of waste inside vault cells (ft)	3
Roof thickness (in.)	45
Exterior wall thickness (in.)	45
Interior wall thickness (in.)	24
End wall thickness (in.)	30
Flood thickness (in.)	51
Specified compression strength of concrete at 28 days (psi)	5,000
Specified yield strength of reinforcement (psi)	60,000
Reinforcement size and space in the vault elements:	
Roof - exterior face, both ways	#7 @ 6" o.c.
Roof - interior face, both ways	#9 @ 6" o.c.
Exterior wall - exterior face, both ways	#8 @ 6" o.c.
Exterior wall - interior face, both ways	#7 @ 6" o.c.
Interior wall - both face, both ways	#6 @ 6" o.c.
End wall - exterior face, both ways	#7 @ 6" o.c.
End wall - interior face, both ways	#7 @ 6" o.c.
Floor - exterior face, both ways	#8 @ 6" o.c.
Floor - interior face, both ways	#10 @ 6" o.c.
Number of vaults in earth-mounded unit (ea)	1
Dimensions of earthen cover at grade (L x W, ft)	810.5 x 568.5
Overall waste placement efficiency in cell (percent)	41[b]
Earth cover thickness (ft)	33
Nominal earthen cover above grade (ft)	

a. Ignoring 2 feet floor overhang from paces of exterior walls.

b. Depending on container type.

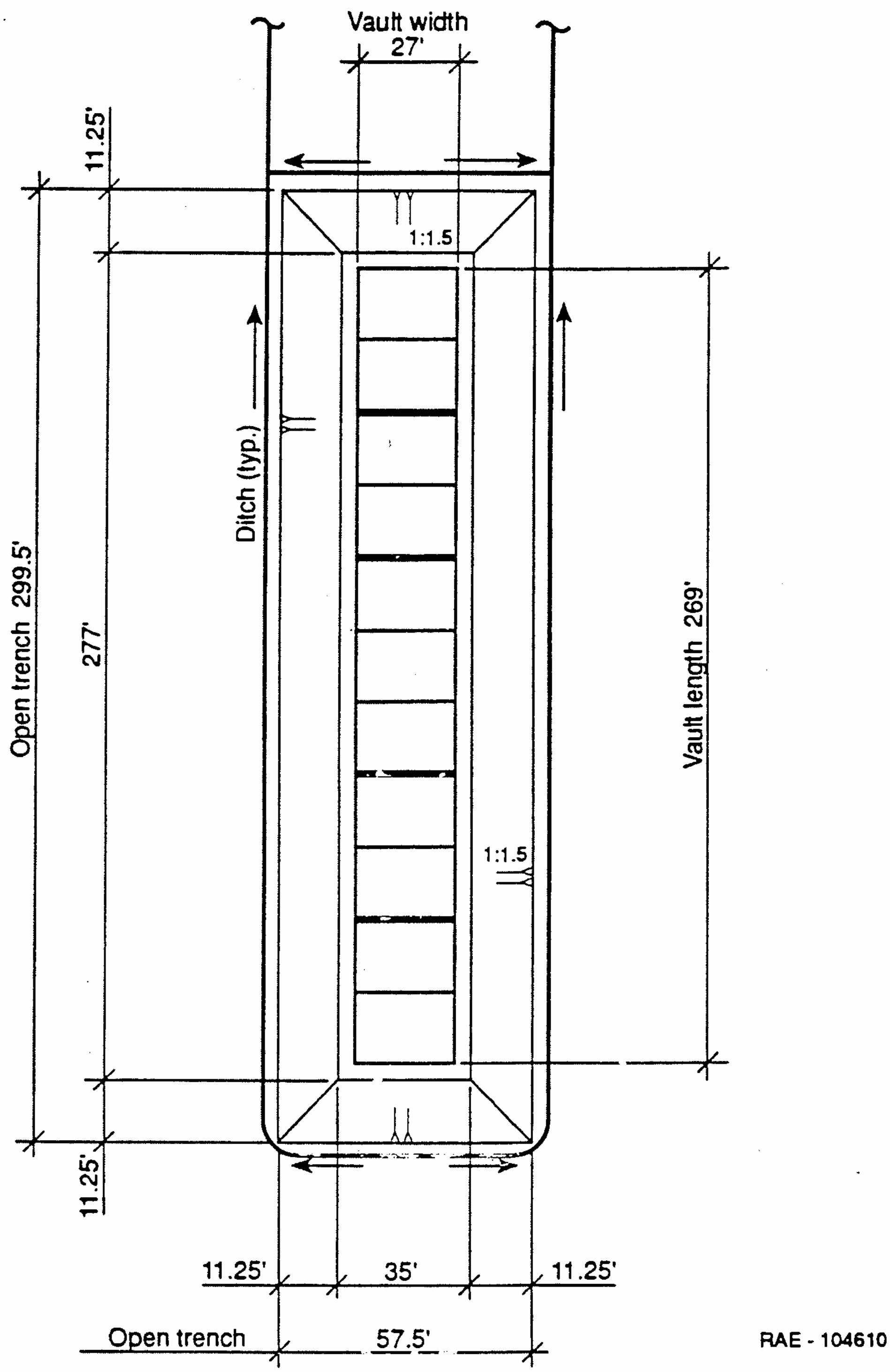

Figure 4-12. Aboveground vault disposal unit.

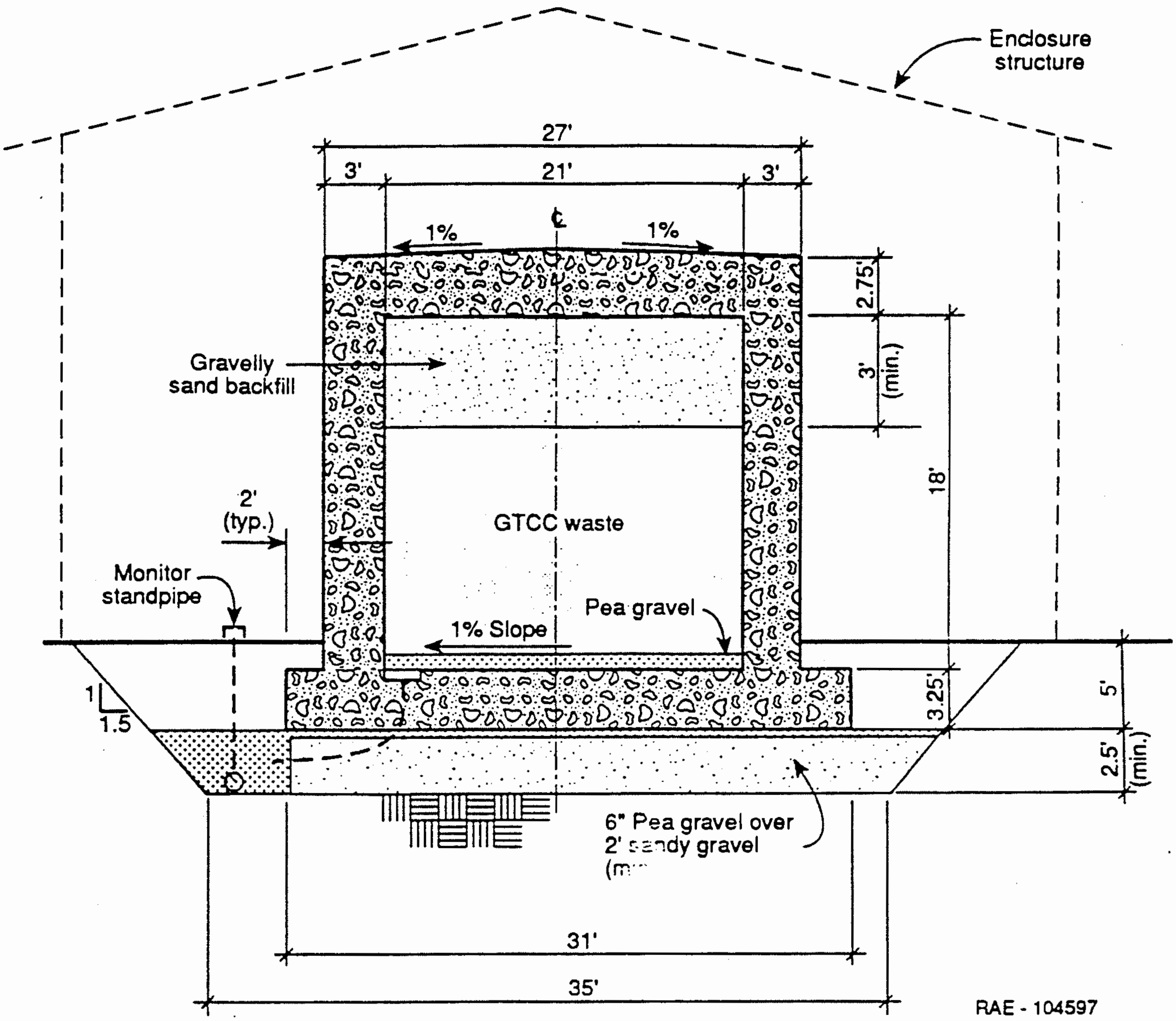

Figure 4-13. Cross section of aboveground vault.

waste. A freestanding building protects the exterior of the vault from exposure to precipitation, temperature extremes, and erosive forces. This building will require maintenance for at least 100 years after closure. A summary of disposal facility and disposal unit characteristics for the aboveground vault disposal concept is provided in Table 4-13.

Intermediate-Depth and Deep Geologic Disposal Concepts. The intermediate-depth and deep geologic GTCC LLW disposal concepts include the mined cavity and drilled hole facilities. The design of each concept is the same for the two disposal depths. Features common to these concepts are discussed here, specific design characteristics of each concept are provided below.

The mined cavity and drilled hole disposal concepts include support facilities for administration, operations, access control, maintenance, decontamination, and waste receiving/storage as discussed in Section 4.3.3. The specific dimensions of these facilities and the land requirements differ between disposal concepts. These differences are considered below.

The intermediate-depth and deep geologic disposal concepts will utilize engineered cover systems, shown in Figure 4-14. The final cover will consist of (in ascending order):

- A 15.2 cm (6 in.) layer of gravelly sand
- A 0.9 m (3 ft) layer of compacted bentonite clay
- A layer of geotextile
- A 0.3 m (1 ft) layer of gravel/cobble
- A 15.2 cm (6 in.) layer of pea gravel
- A 15.2 cm (6 in.) layer of sand
- A 0.3 m (1 ft) layer of vegetated topsoil.

Table 4-13. Summary of disposal site and disposal unit physical characteristics for the aboveground vault disposal concept.

Characteristic	Value
Overall site dimensions (ft x ft)	1120 x 1870
Total site area (ac)	48
Disposal area dimensions (ft x ft)	620 x 1270
Total disposal area (ac)	18
Number of disposal unit or vault (ea)	4
GTCC LLW disposal unit	
Number of cells per vault (ea)	11
Interior cell dimensions (L x W x H, ft)	21 x 21 x 18
Exterior vault dimensions (L x W x H, ft)	269 x 27 x 24[a]
Backfill thickness on top of waste inside vault (ft)	3
Roof thickness (in)	33
Exterior wall thickness (in)	36
Interior wall thickness (in)	24
End wall thickness (in)	30
Flood thickness (in)	39
Specified compression strength of concrete at 28 days (psi)	5,000
Specified yeild strength of reinformcenet (psi)	60,000
Reinforcement size and space in the vault elements:	
Roof- exterior face, both ways	#7 @ 6" o.c.
Roof - interior face, both ways	#9 @ 6" o.c.
Exterior wall - exterior face, both ways	#8 @ 6" o.c.
Exterior wall - interior face, both ways	#7 @ 6" o.c.
Interior wall - both face, both ways	#6 @ 6" o.c.
End wall - exterior face, both ways	#7 @ 6" o.c.
End wall - interior face, both ways	#7 @ 6" o.c.
Floor - exterior face, both ways	#8 @ 6" o.c.
Floor - interior face, both ways	#10 @ 6" o.c.
Minimum trench excavation depth (ft)	7.5
Trench excavation at grade (L x W, ft)	299.5 x 57.5
Trench excavation at base (L x W, ft)	
Overall waste placement efficiency in cell (percent)	41[b]
Earth cover thickness (ft)	0

a. Ignoring 2 feet floor overhang from faces of exterior wall.

b. Depending on container type.

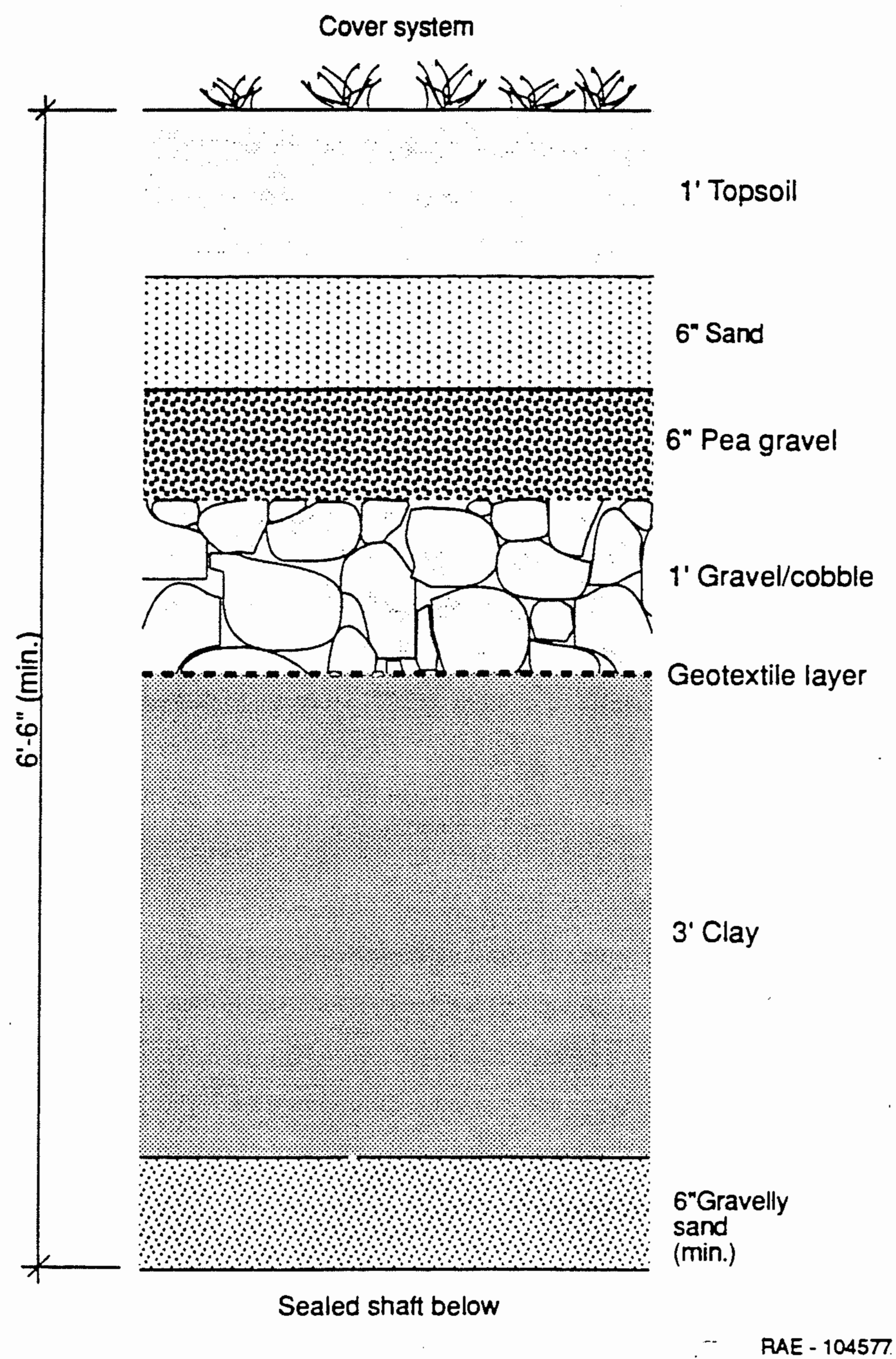

Figure 4-14. Shaft cover system for intermediate-depth or deep geologic disposal unit.

Mined-Cavity Disposal Concept. The surface layouts for the mined cavity disposal concept for the intermediate-depth and deep geologic facilities are shown in Figure 4-15. The outer perimeter of the facility at the ground surface measures approximately 585 by 900 m (1,920 by 2,960 ft).

The centerpiece of the mined cavity is the waste handling and ventilation building. Receipt of the modular concrete canisters and preparation of the canisters for disposal take place here. The building houses the waste preparation equipment, and the hoist and ventilation equipment for the three shafts. Each of these shafts will be used alternatively for personnel/material and ventilation.

A cross sectional view of the proposed shaft design is shown in Figure 4-16. The circular shaft has an inside diameter of 6.1 m (20 ft), the walls of which will be lined with 38 to 46 cm (15 to 18 in.) of reinforced concrete. The shaft liner will extend about 1.1 m (3.5 ft) above the ground surface for worker safety considerations. The shaft is designed to accommodate a 3 by 4.9 m (10 by 16 ft) rectangular cage for transporting equipment and material, as well as conduits for power, light, and communications cables. Additionally, the shaft design includes access for two pre-placed monitoring wells. These wells will allow sampling of the drainage sump located at the bottom of the shaft. A high-efficiency suction pump will provide the capacity to remove leachate from the disposal units through the monitoring wells.

A cross sectional view of the mined-cavity disposal concept tunnel is provided in Figure 4-17. The tunnel is 6.1 m (20 ft) wide and 9.8 m (32 ft) high, and is lined with a minimum of 0.3 m (1 ft) of reinforced concrete to protect workers from falling debris and to control water infiltration during tunnel construction and operation. The tunnels are designed to accommodate modular concrete canisters stacked two high and two wide in a staggered configuration. The tunnels will also accommodate a mobile, overhead crane to allow placement of the waste. Tunnels extend 190 m (620 ft) outward from the access shaft and are designed with a 1 percent slope and a gravel drainage layer to allow drainage back toward the monitoring sump at the bottom of the shaft.

Longitudinal sections of the mined-cavity disposal concept for the intermediate-depth and deep geologic facilities are shown in Figures 4-18 and 4-19, respectively. These figures, which show the facilities in their closed condition, differ only in terms of the distance from the top of the bedrock to the top of the mined tunnels. In the intermediate-depth facilities this distance is 61 m (200 ft), while in the deep geologic setting it is 275 m (900 ft).

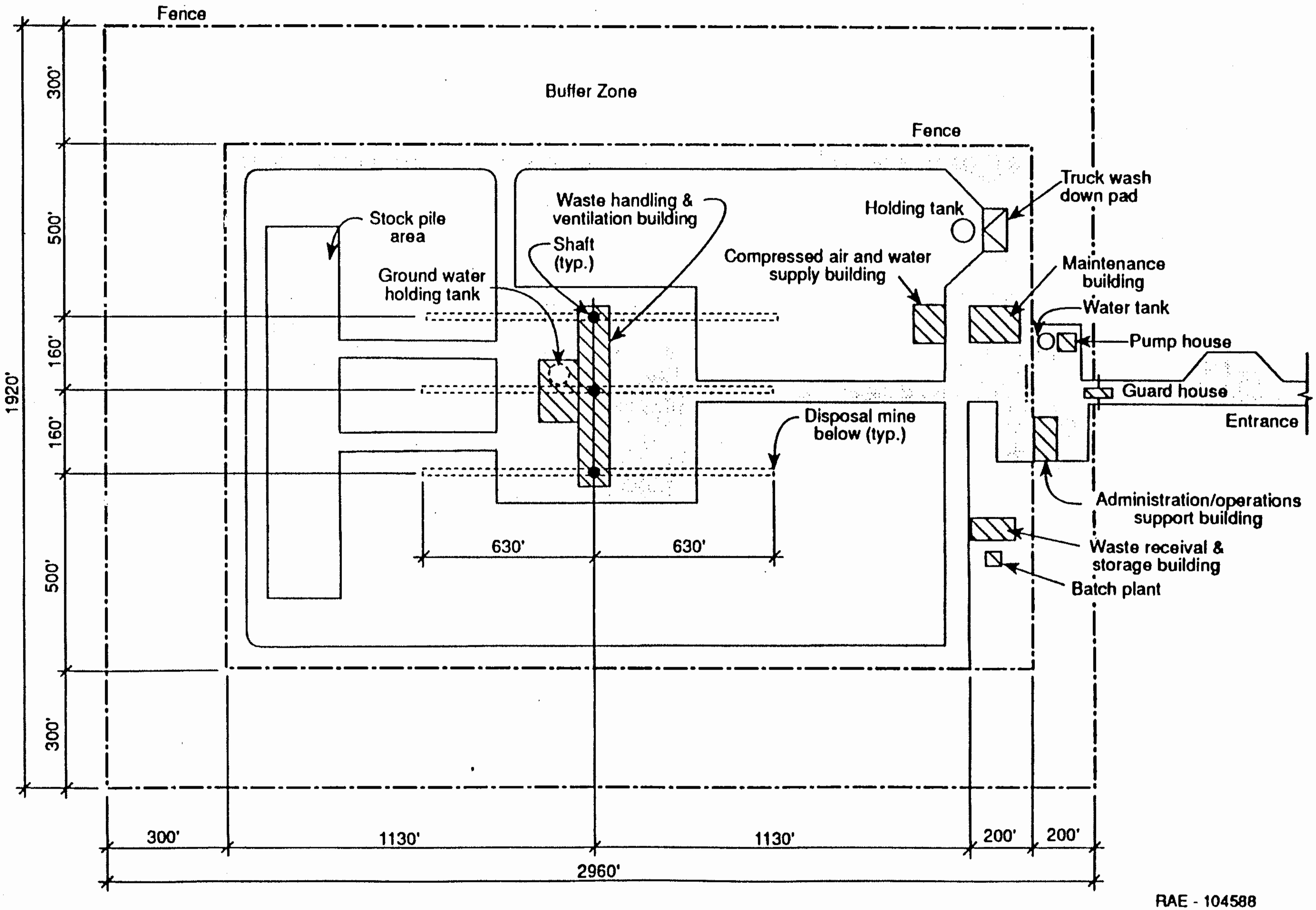

Figure 4-15. Intermediate-depth or deep geologic mine disposal facility layout plan.

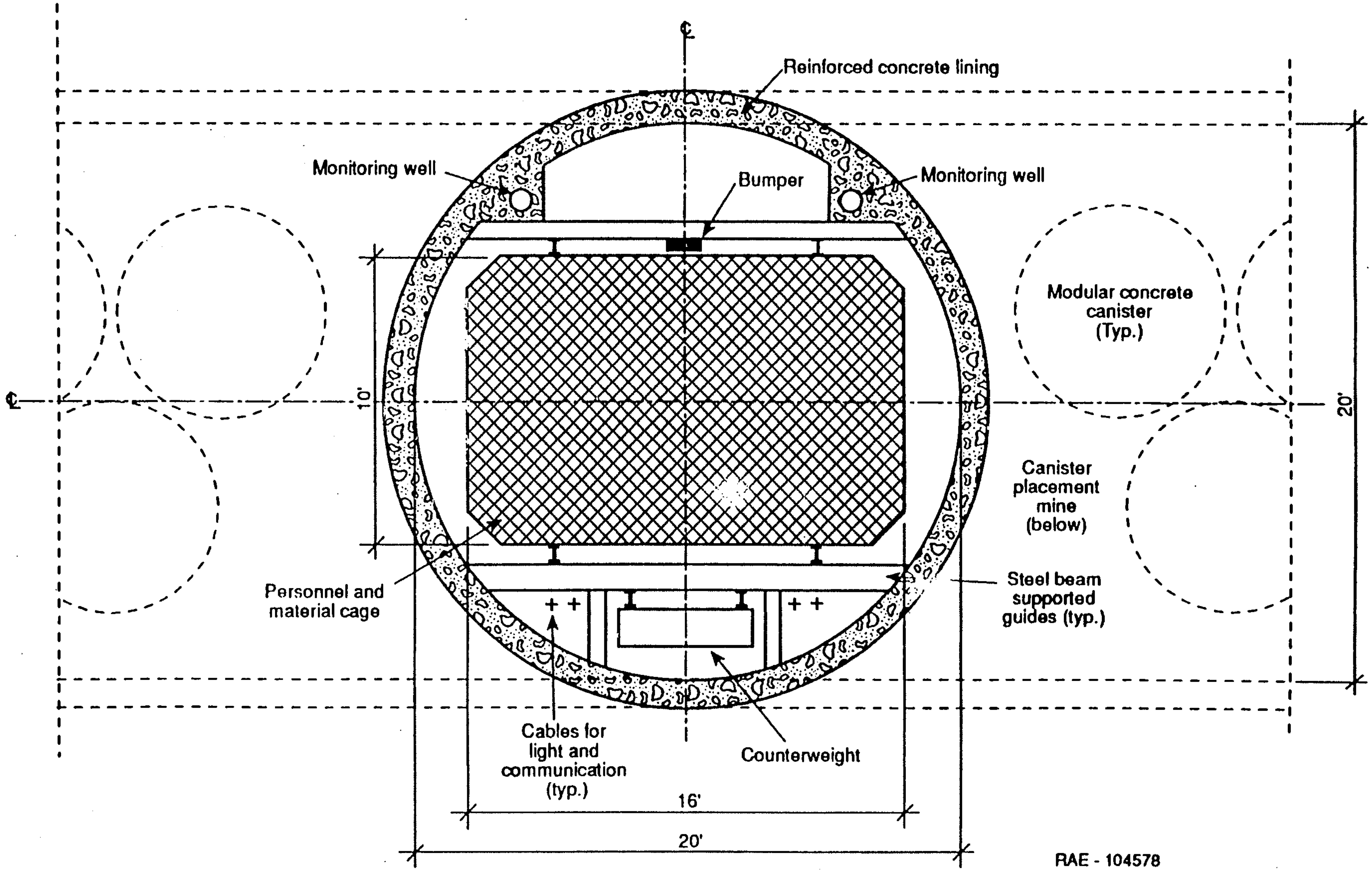

Figure 4-16. Cross-section of personnel and material shaft to be used during operations of intermediate-depth or deep geologic mine.

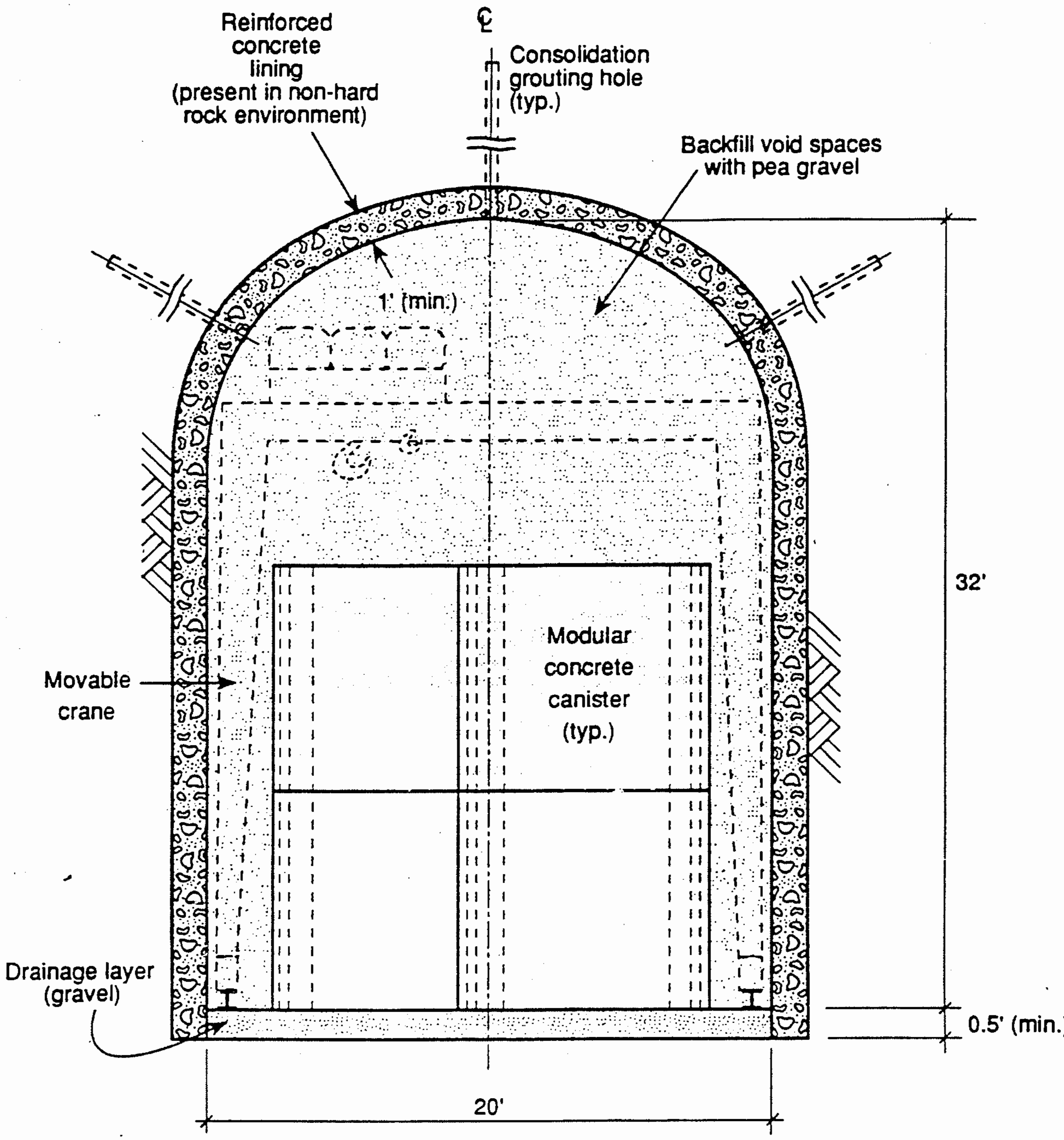

Figure 4-17. Cross section of mine disposal.

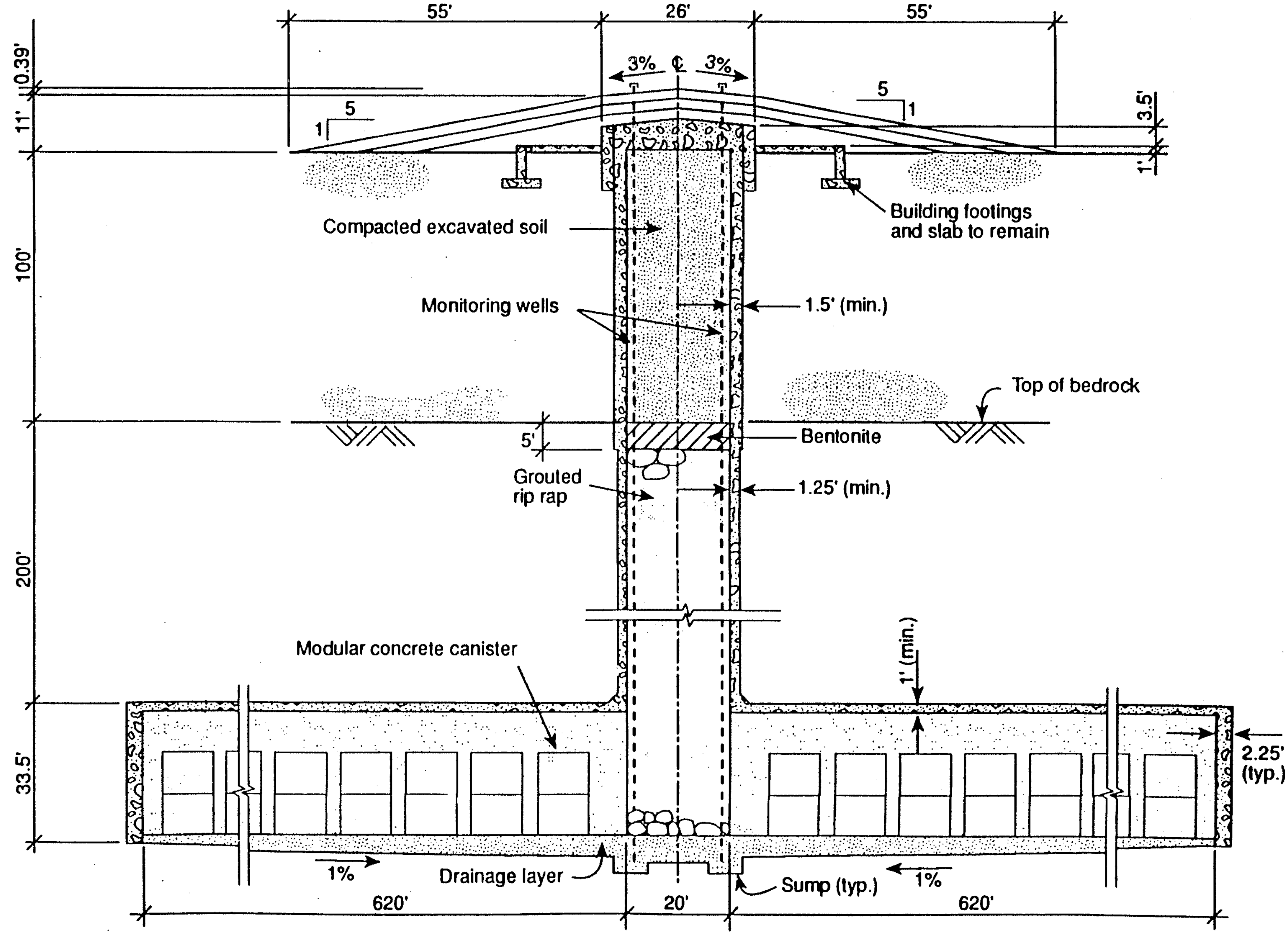

Figure 4-18. Longitudinal section for intermediate-depth mine disposal.

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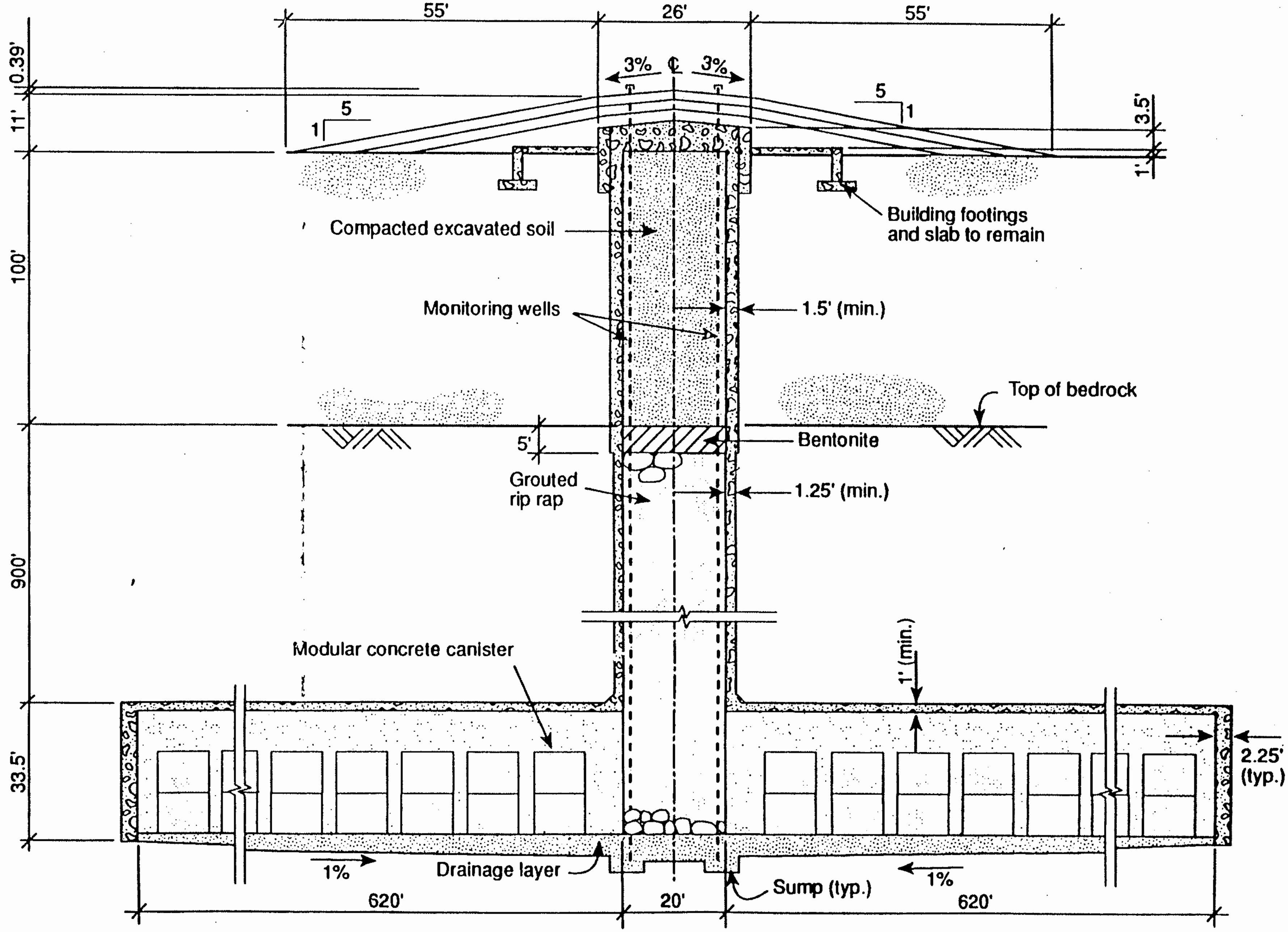


Figure 4-19. Longitudinal section for deep geologic mine disposal.

Waste-filled concrete canisters will be placed in the mined tunnels using an overhead crane. Void spaces around the canisters will be backfilled with pea gravel. The portion of the vertical shaft in the bedrock will be backfilled with non-weathered riprap excavated during the construction of the facility. Void spaces between the riprap will be pressure grouted to provide the best possible seal. Several rows of keyways will be constructed on the interior surface of the shaft to provide additional support and bonding between the grouted riprap and the shaft liner.

The vertical shaft in the top 1.5 m (5 ft) ft of bedrock will be backfilled with bentonite clay. The expansive characteristics of this material in the presence of water will assist in providing a good seal against subsequent water infiltration into the closed disposal units. The top 30 m (100 ft) of the vertical shaft will be backfilled with material that was excavated during facility construction and compacted to minimize the potential for subsidence. The precautions taken in backfilling the vertical shaft are assumed to be adequate to prevent the flow of water through the shaft to the disposal horizon.

The surface buildings at the facility will be removed, although the footings and foundation slab will remain, and the shaft will be sealed with a sloped (3 percent slope) concrete plug. These concrete plugs will be covered by an engineered cover system, described earlier. The characteristics of the mined cavity disposal concept are summarized in Table 4-14.

Drilled Hole Disposal Concept. The surface layouts for the drilled hole disposal concept for the intermediate-depth and deep geologic disposal facilities are shown in Figure 4-20. The outer perimeter of the facility at ground surface measures approximately 730 by 655 m (2,400 by 2,150 ft).

The drilled holes are in four groups of twenty in a 2 by 10 configuration. Holes will be placed approximately 1.5 m (5 ft) apart to provide structural independence. A cross section of a drilled hole is shown in Figure 4-21. The hole will be approximately 3 m (10 ft) in diameter with a monitoring well access tube placed to one side. Vertical sections of the drilled hole are shown in Figures 4-22 and 4-23 for the intermediate-depth and deep geologic facilities, respectively. The only difference between these figures is the depth at which waste placement begins. In the intermediate-depth facility waste is placed to within 91 m (300 ft) of the ground surface, while in the deep geologic setting the waste is placed to within 305 m (1,000 ft).

Table 4-14. Summary of disposal facility and disposal unit parameters for the mine disposal concept.

Characteristic	Value
Overall site dimensions (ft x ft)	2960 x 1920
Total site area (ac)	130
Minimum effective buffer zone (ft)	800
Nominal diameter for vertical shaft (ft)	20
Minimum liner thickness for shaft in unconsolidated material (ft)	1.5
Minimum liner thickness for shaft in bedrock (ft)	1.25
Minimum liner thickness for tunnel section (ft)	1.0
Minimum liner thickness for end wall of tunnel (ft)	2.25
GTCC LLW disposal tunnels or mines	
Nominal width of tunnel or mine	20
Nominal height (ft)	32
Nominal length of tunnel or mine, each end (ft)	620
Number of tunnels or mines (ea)	6
For intermediate-depth disposal	
Unconsolidated material depth (ft)	100
Overburden bedrock depth (ft)	200
Nominal distance from disposal tunnel or mine to native grade (ft)	300
For deep geologic disposal	
Unconsolidated material depth (ft)	100
Overburden bedrock depth (ft)	900
Nominal distance from disposal tunnel or mine to native grade (ft)	1,000

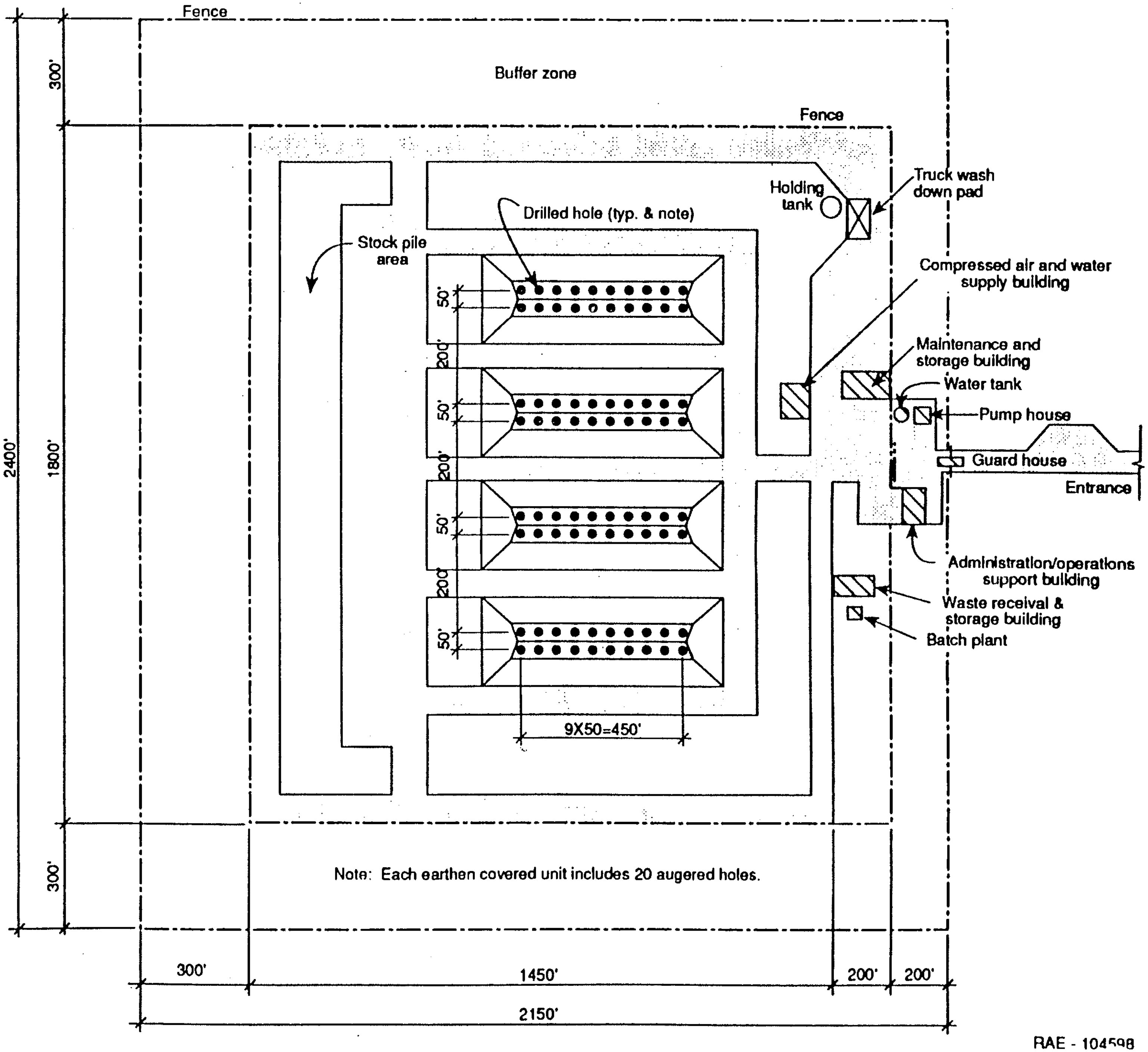


Figure 4-20. Intermediate-depth or deep geologic shaft disp
facility - surface facility layouts.

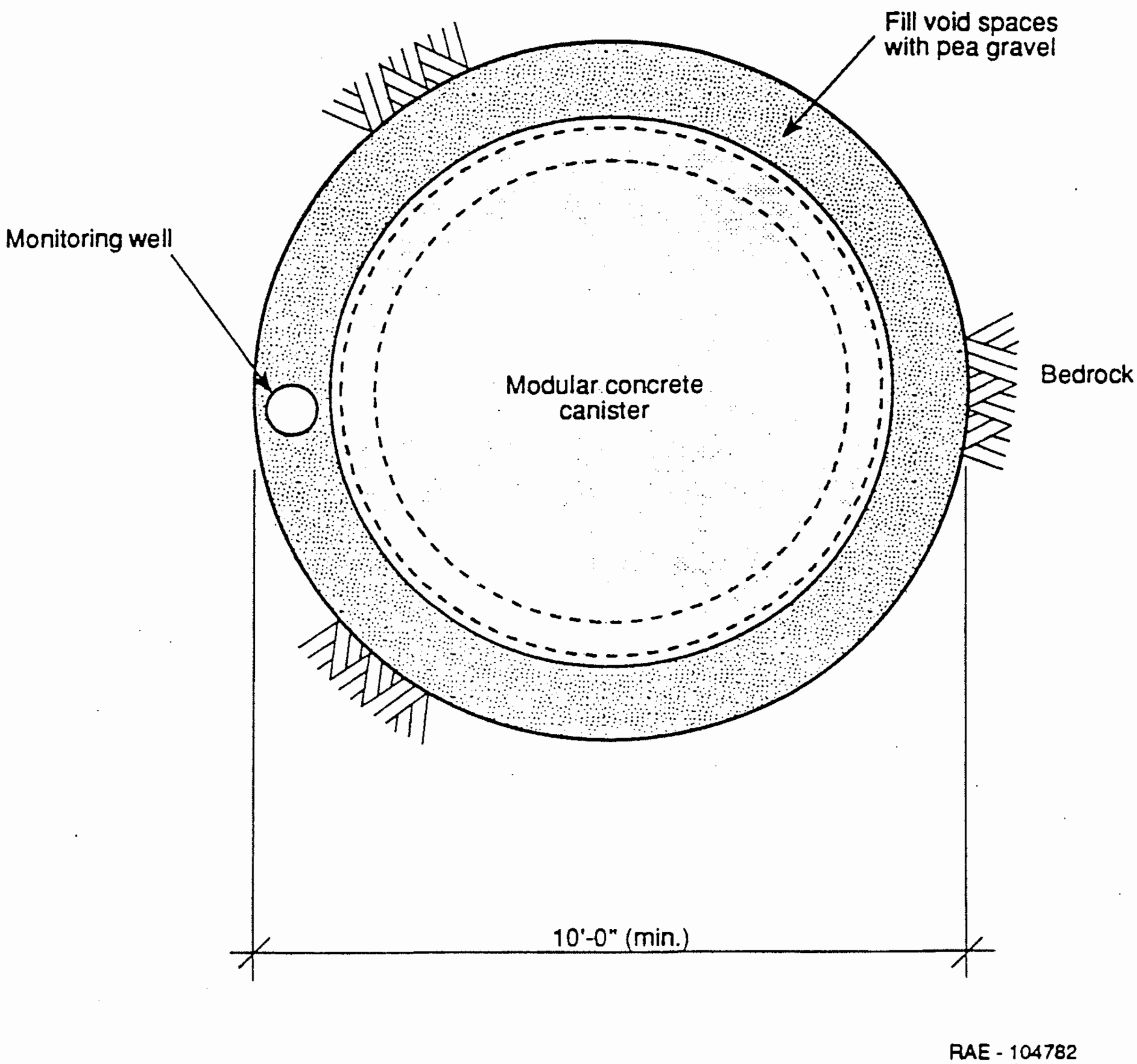


Figure 4-21. Horizontal section of shaft disposal unit for modular concrete canister.

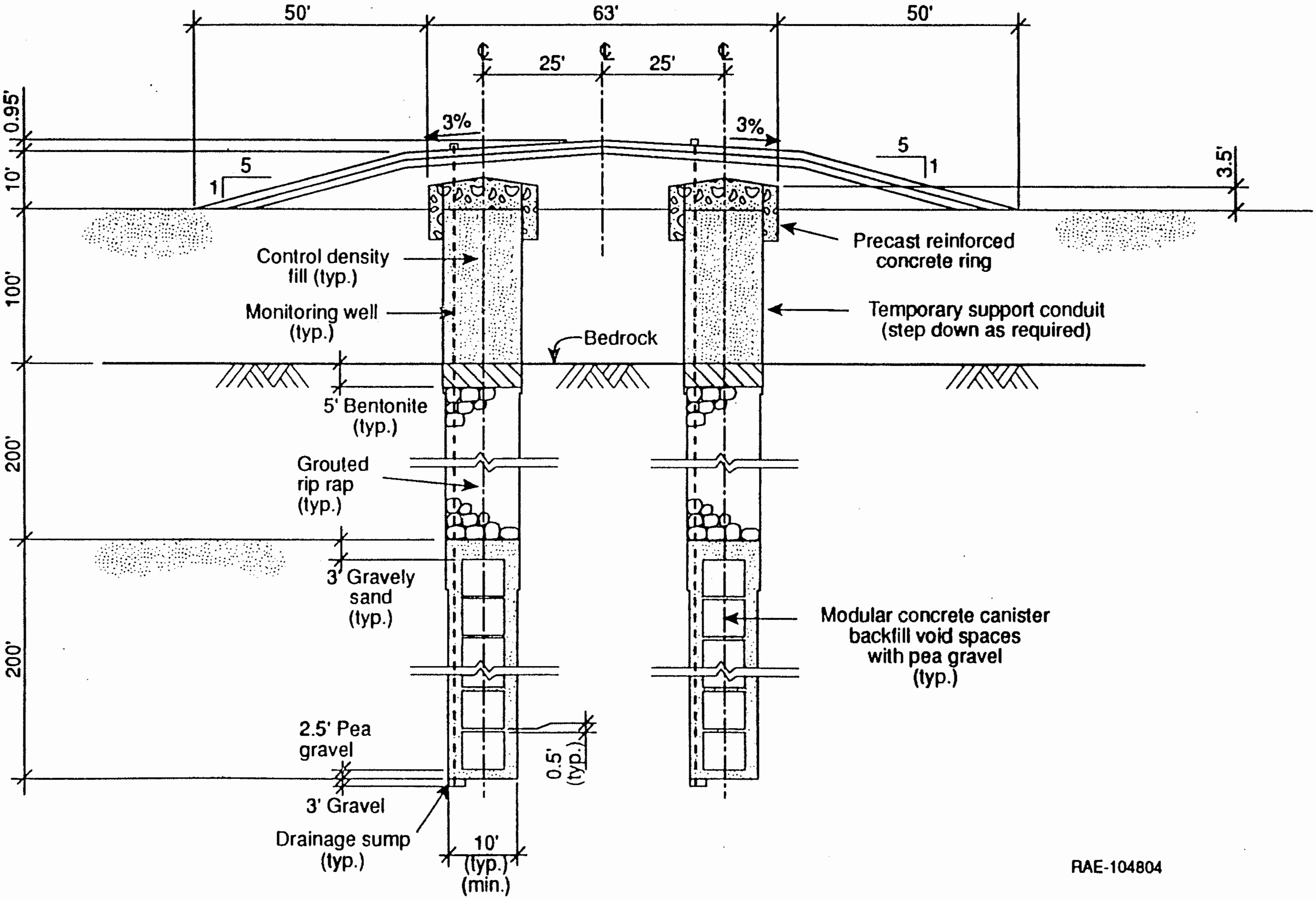


Figure 4-22. Vertical section for intermediate-depth augered hole disposal.

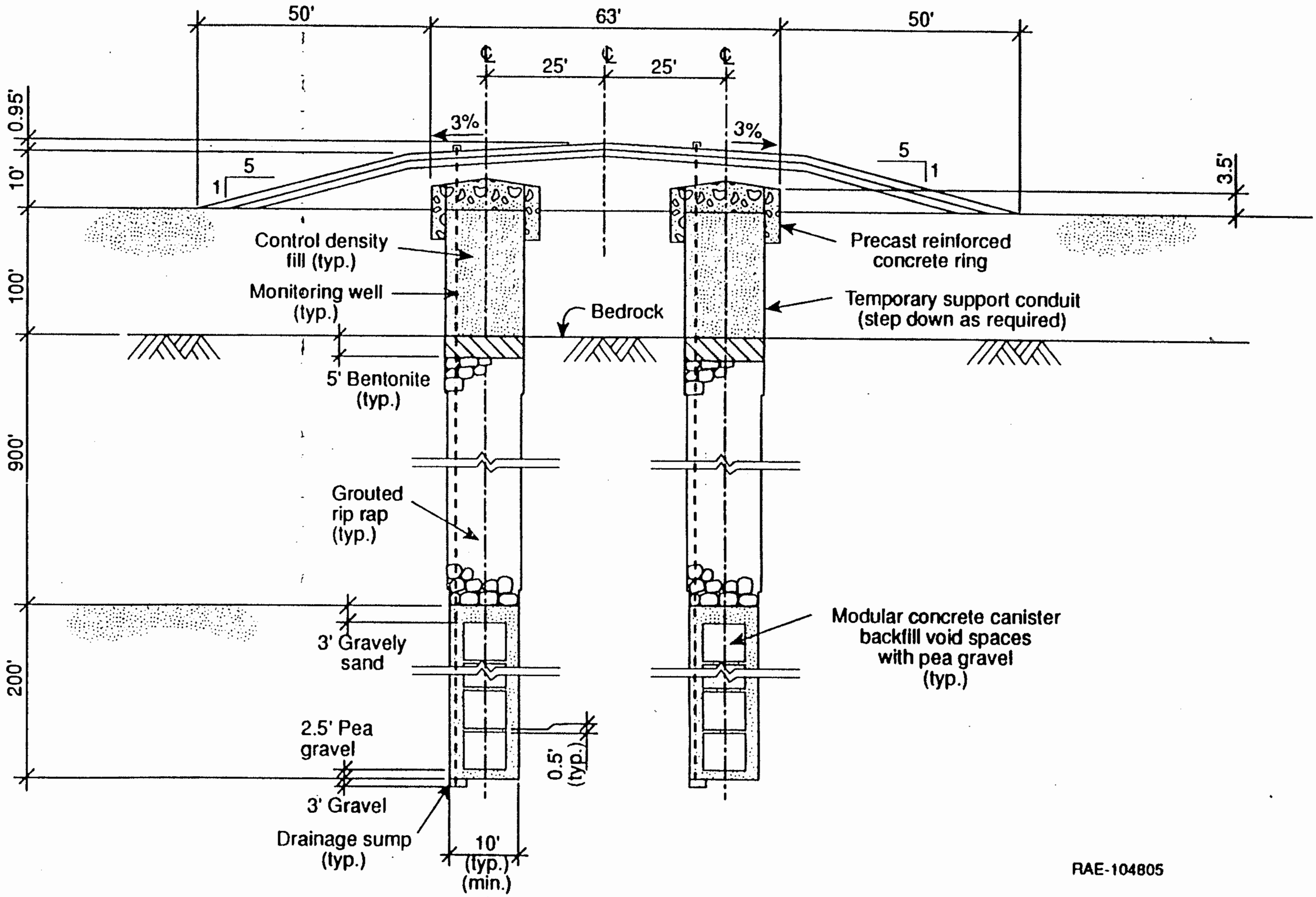


Figure 4-23. Vertical section for deep geologic augered hole disposal.

The holes are assumed to be constructed using conventional drilling methods. Temporary steel conduits will be used to support unconsolidated material in the drilled holes. These conduits will be removed and reused during backfill processing. During drilling processes, the bentonite slurry may be used for stabilization of non-cohesive soil layers. A pre-casted reinforced concrete ring is installed at the hole opening and extends about 1.4 m (4.5 ft) above ground surface for worker safety considerations.

Following acceptance of waste-filled modular concrete canisters for disposal, the canisters will be lowered into the drilled hole. It is assumed that no workers are present inside the drilled hole during either construction or operation of the concept. Waste in concrete canisters is placed in a 61 m (200 ft) thick layer. Void spaces between and around the canisters are filled with pea gravel. The filled holes are backfilled with grouted riprap to a point just below the top of the bedrock. The top 1.5 m (5 ft) of the bedrock will be filled with a layer of compacted bentonite clay. The top 30 m (100 ft) of the hole will be backfilled with material excavated during facility construction and compacted to minimize the potential for subsidence. The precautions taken in backfilling the drilled holes are assumed to be adequate to prevent the flow of water through the holes to the disposal horizon.

The surface buildings at the facility will be removed, although the footings and foundation slab will remain, and the shaft will be sealed with a sloped (3 percent slope) concrete plug. These concrete plugs will be covered by an engineered cover system. Each of the four groups of holes will have its own engineered cover system. The characteristic of the conceptual drilled hole disposal facility are summarized in Table 4-15.

4.4 Characteristics of the Hypothetical GTCC LLW Disposal Sites

In order to judge the performance of the 13 GTCC LLW disposal concepts, a range of environmental settings in which the disposal concepts could be located was defined. Hypothetical arid and humid sites are used to describe a range of possible site conditions. These characteristics are used to determine several parameters that are key to the performance of the disposal concepts, including:

- Failure times of the concrete barriers
- Release rates due to advection and diffusion
- Travel time to the aquifer and to the hypothetical well

Table 4-15. Summary of disposal facility and disposal unit parameters for the augered hole concept.

Parameter	Value
Overall site dimensions (ft x ft)	2150 x 2400
Total site area (ac)	118
Minimum effective buffer zone (ft)	800
GTCC LLW drilled hole disposal unit	
Minimum diameter (ft)	10
Nominal disposal length (ft)	200
Number of drilled holes (ea)	80
Minimum spacing of holes on center (ft)	50
Number of holes in earthen cover unit (ea)	20
Number of earthen cover unit (ea)	4
Nominal concrete plug or cap above grade (ft)	3.5
Minimum earthen cover thickness (ft)	6.5
Number of modular concrete canister in drilled hole unit (ea)	20
For intermediate-depth disposal	
Unconsolidated material depth (ft)	100
Nominal distance from waste disposal layer to top of bedrock	200
Nominal distance from waste disposal layer to native grade (ft)	300
For deep geologic disposal	
Unconsolidated material depth (ft)	100
Nominal distance from waste disposal layer to top of bedrock (ft)	900
Nominal distance from waste disposal layer to native grade (ft)	1,000

- Dilution of released activity in the aquifer

- The probability of intrusive events

- The consequence of intrusive events.

The following sections present the characteristics of the hypothetical arid and humid sites used in the technical evaluation. Existing information for a number of actual and humid sites were used to build these descriptions. The information was modified to represent sites where three acceptable disposal horizons, near surface, intermediate depth, and deep geologic, could be found. Both hypothetical sites are described only to the extent necessary to support the technical evaluation of the 13 GTCC LLW disposal concepts.

4.4.1 Hypothetical Arid Site

The arid site presents many advantages to waste disposal; low rates of percolation and great distances to groundwater are two of these. The site is representative of the Basin and Range Province of the western United States where the precipitation rate is low and percolation is limited by the high rate of evapotranspiration. The site is underlain by a thick sequence of unsaturated alluvial deposits. Depth to groundwater is great in this region and the rate of groundwater flow is low. Figure 4-24 presents the general configuration of the arid site.

The site is located in a northwest-trending valley in the Basin and Range Province. The valley is bounded by block-faulted mountains composed of lower Paleozoic rocks and Tertiary volcanoes. The valley was formed by normal faulting along the mountain fronts and slopes to the southeast. Moderate to steep sloping alluvial fans have formed along the mountain fronts. The hypothetical GTCC LLW disposal facility is found along one side of the valley, about halfway up the gently sloping valley wall. The site is considered to be geomorphologically stable, with constructive sedimentary processes at work. Destructive geomorphic processes such as mass wasting, slumping, debris flows, and land sliding are not operative on the gentle slopes of the area.

Meteorology. The climate is typical of a desert with hot summer days and cool nights. The mean yearly temperature measured over a three year period was approximately 19°C. Mean daily temperatures typically range from 25 to 34°C during the summer (June-August), and from 2 to 15°C

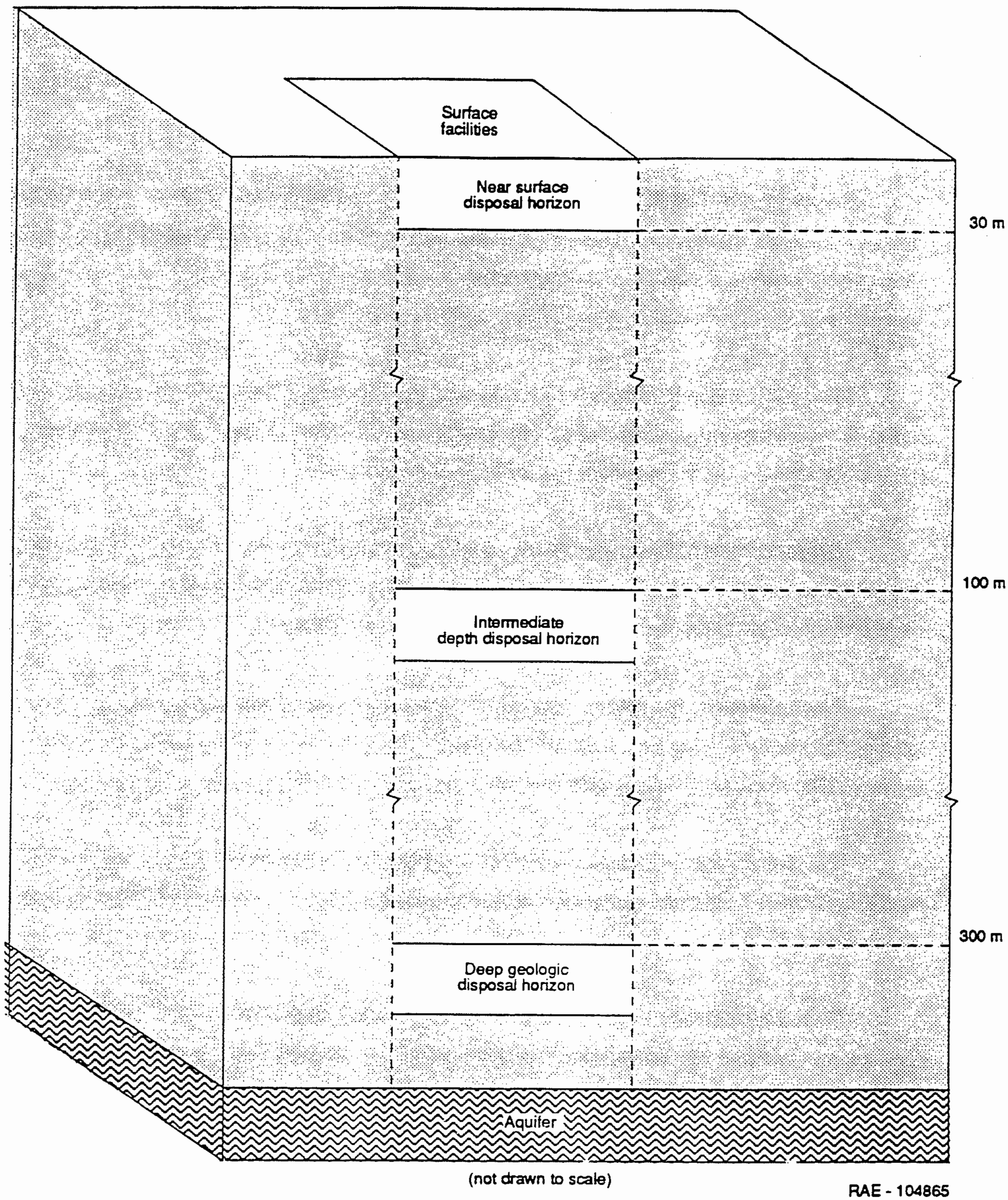


Figure 4-24. General configuration of the hypothetical arid site.

during the winter (December-February). Eight to 13 freeze-thaw cycles occur annually, with an average of 8 cycles/yr. Mean annual at the site precipitation ranges from 7.4 to 11.4 cm (2.9 to 4.5 in.). Average monthly estimates for potential evapotranspiration range from about 4 cm (1.6 in.) in December to 33 cm (13 in.) in July.

Geology and Seismology. Surficial deposits of unconsolidated alluvium are about 60 m (183 ft) thick and extensive. Thickness of the alluvium increases to the southeast and decreases to the northwest. Beneath the alluvium lies approximately 2,400 m (7,315 ft) of tuff. Table 4-16 lists the radionuclide specific retardation factors for the hypothetical arid site.

The site is located in a region of low to moderate seismicity. Present stress configurations have existed for at least several million years. Results of potassium-argon dating of ash layers indicate little tectonic deformation in the region during the last 7-12 million years.

Surface Water. There is no surface water in the area of the site. The site is located in an arid region where runoff is relatively infrequent and stream flow is ephemeral in nature. The site is located well above the flood plain for any conceivable flood recurrence interval.

Groundwater. Percolation rates at the near surface, and intermediate and geologic depths average 0.5 mm/yr (0.18 in./yr). Depth to the aquifer is approximately 457 m (1,500 ft) below the land surface. The horizontal gradient in the aquifer is approximately 5.9E-04 m/m (1.9E-03 ft/ft).

The groundwater within the aquifer has a relatively homogeneous chemistry, dominated by sodium. Table 4-17 lists the concentrations of chemical constituents critical to the lifetime of concrete structures.

Groundwater quality is good and total dissolved solids concentrations are less than 600 mg/L. Tritium data indicate that groundwater has been isolated from present-day atmospheric conditions or recharge for at least the past 60 years.

The characteristics for the hypothetical arid GTCC LLW disposal site are summarized in Figure 4-25. The base case values and parameter ranges shown in the figure were used in the performance evaluation of the GTCC LLW disposal concepts and the sensitivity analysis, respectively.

Table 4-16. Radionuclide retardation factors for the hypotheticl arid site.

Radionuclide	Base Case	Range	Source
H-3	1	1 to 1	EPA88
C-14	1	1 to 1	EPA88
Mn-54	20,000	15,000 to 60,000	a
Fe-55	20,000	15,000 to 60,000	EPA88
Co-58	500	400 to 50,000	EPA88
Ni-59	5,000	500 to 10,000	b
Co-60	500	400 to 50,000	EPA88
Ni-63	5,000	500 to 10,000	b
Zn-65	50	20 to 500	c
Sr-90	200	20 to 10,000	NAS83
Nb-94	5,000	500 to 10,000	b
Tc-99	5	1 to 100	NAS83
I-129	1	1 to 1	NAS83
Cs-134	500	60 to 10,000	NAS83
Cs-137	500	60 to 10,000	NAS83
Ce-141	5,000	500 to 10,000	d
Ce-144	5,000	500 to 10,000	d
Pu-238	200	50 to 5,000	NAS83
Pu-239	200	50 to 5,000	NAS83
Pu-240	200	50 to 5,000	NAS83
Am-241	1,000	300 to 50,000	NAS83
Pu-241	200	50 to 5,000	NAS83
Cm-242	500	100 to 10,000	NAS83

a. Assumed to be same as Fe based on chemical similarities, value from EPA88 used.

b. Assumed to be same as Zr based on chemical similarities, value from NAS83 used.

c. Assumed to be same as Pb based on chemical similarities, value from NAS83 used.

d. Assumed to be same as Th based on chemical similarities, value from NAS83 used.

Table 4-17. Concentrations of critical constituents at the humid site.

Constituent	Concentration (moles/L)		Source
	Average	Range	
Cl-	1.1e-04	1.4E-05 - 4.5E-04	IAEA 1992
CO3--	2.7e-04	5.0E-05 - 5.0E-04	Assumed
Mg++	1.6e-05	4.1E-07 - 1.2E-04	IAEA 1992
SO4--	2.1e-05	2.1E-06 - 2.1E-04	IAEA 1992
O2--	1.2e-04	6.3E-05 - 3.6E-04	Assumed

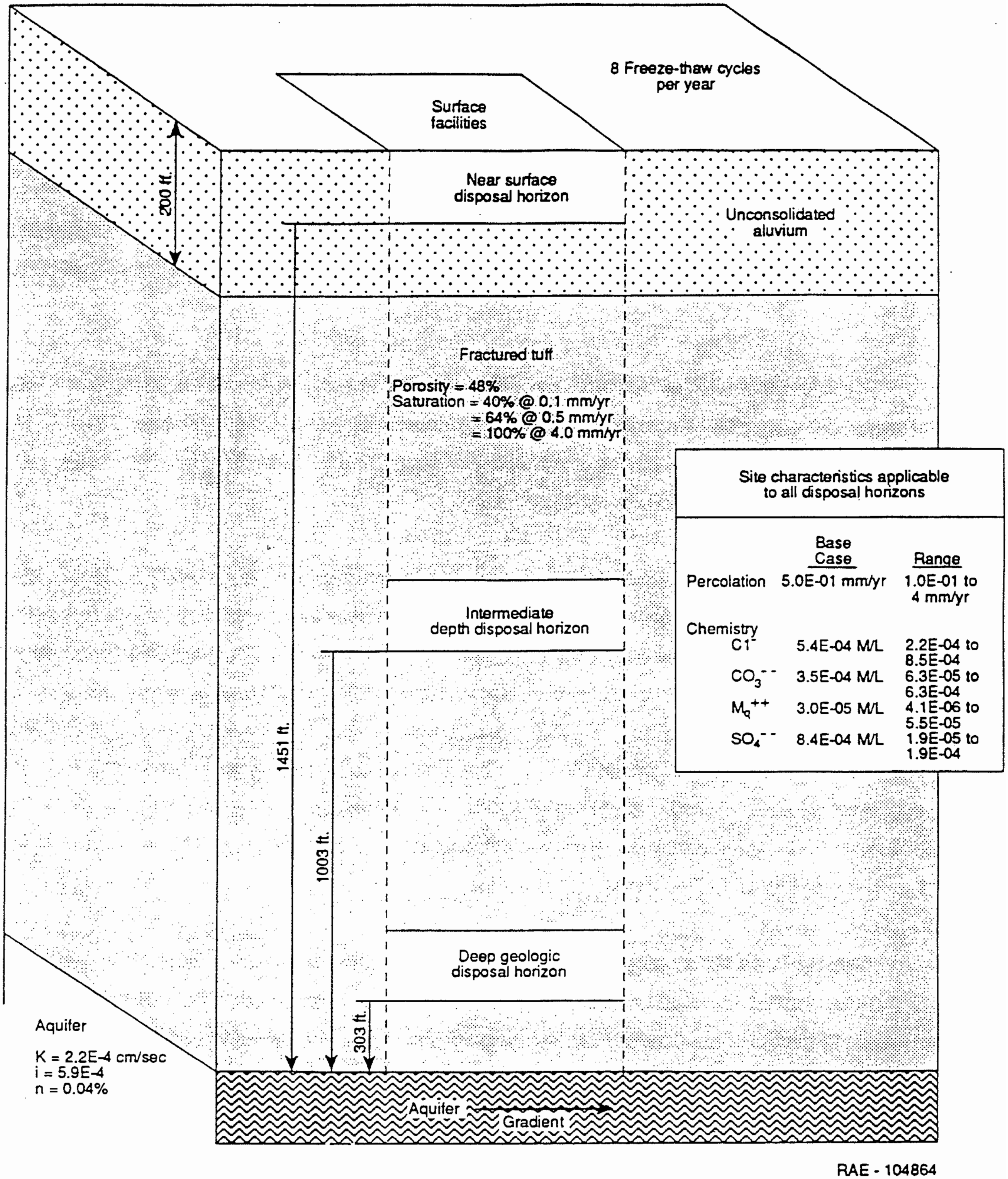


Figure 4-25. Summary of hypothetical arid site characteristics.

4.4.2 Hypothetical Humid Site

The hypothetical humid GTCC LLW disposal site is more complex than the arid disposal site. It is a saturated system made up of a several aquifers with aquitards between them. The hypothetical humid site is located on the Coastal Plain in the southeastern United States and is underlain by thick sedimentary deposits. These deposits overlie a basement complex of consolidated rocks. This region receives a considerable amount of precipitation and the depth to the uppermost aquifer is relatively shallow.

The site is located in the Atlantic Coastal Plain province, approximately 125 km (78 miles) inland. The topography is generally flat to slightly rolling with altitudes ranging from approximately 70 m (213 ft) at the southern end to 79 m (241 ft) above National Geodetic Datum at the northern end. Figure 4-26 presents the general configuration of the humid site.

Meteorology. The climate in the site area is characterized as being humid-subtropical. It is dominated by moist maritime air masses flowing from thc western sides of oceanic high pressure cells. Winters are characterized by frequent continental polar air-mass invasions. The number of freeze-thaw cycles per year ranges from 8 to 19, with an average of 12 cycles/yr. The mean annual temperature ranges from a high of 24° to a low of 11°C. Mean annual rainfall is 1.20E+02 cm/yr (47 in./yr) and precipitation is distributed throughout the year. The mean annual evaporation is 1.38E+02 cm/yr (54 in./yr). Average annual humidity in the region is 66%, with an average minimum of 43% and an average maximum of 90%. The predominate wind direction is from the west-southwest with speeds ranging from 7.2 to 22 km/hr (4.5 to 13.7 miles/hr).

Geology and Seismology. The disposal site is underlain by Atlantic Coastal Plain sediments that include stratified gravel, sand, silt, clay and limestone that range in age from late Cretaceous to Holocene. Thickness of the Coastal Plain sediments ranges from 1 to 2 meters (3 to 6.1 ft) northwest of the site to greater than 1,200 m (3,658 ft) along the coast.

During the late Triassic, extensive normal faulting produced numerous grabens. The rapid accumulation of sediments in the troughs produced tightly cemented red claystone, siltstone, fine-grained sandstone, breccia, and fanglomerate. Weathering has formed a less consolidated clay, silt and sand layer at the surface.

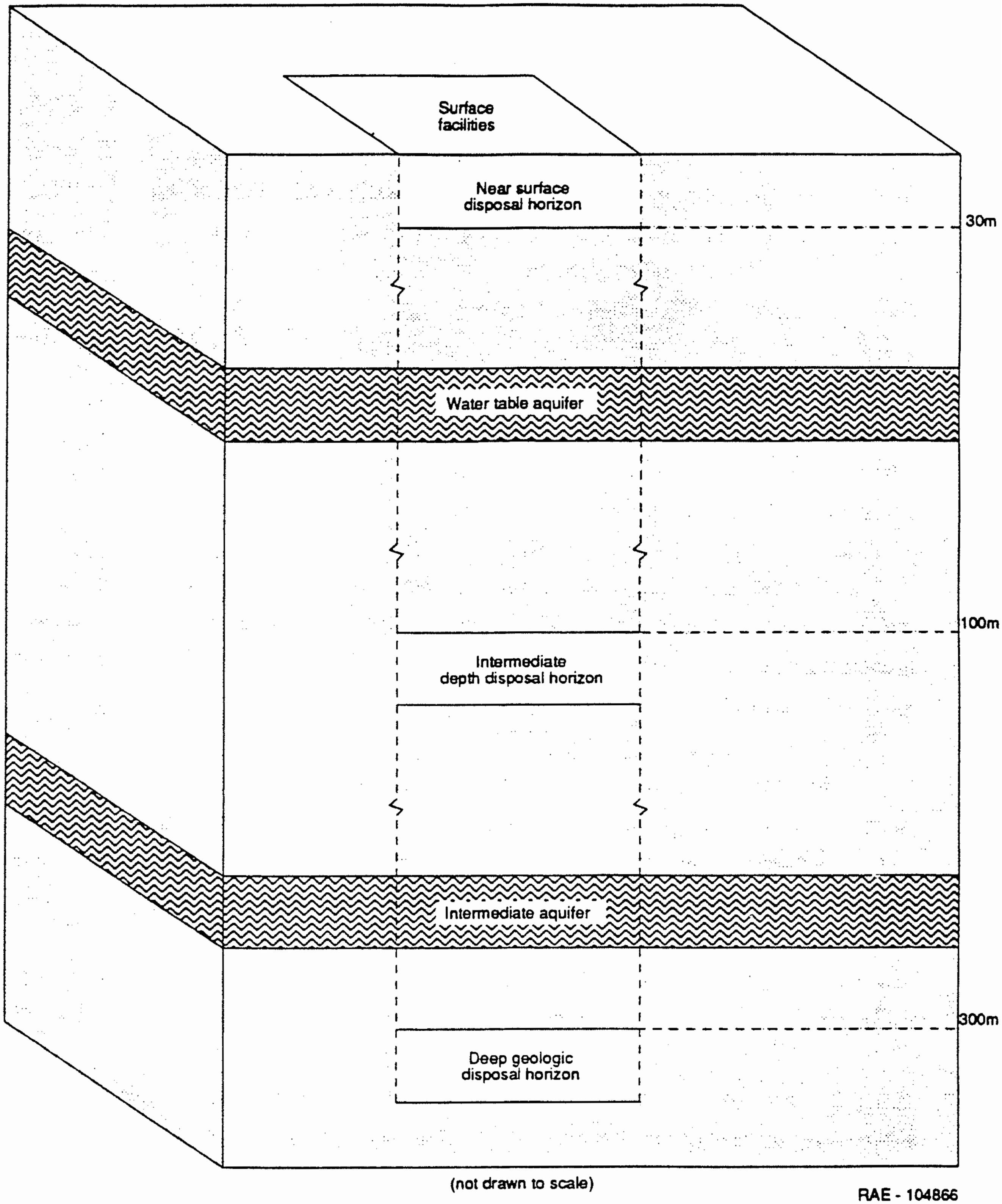


Figure 4-26. General configuration of the hypothetical humid site.

The Triassic bedrock is overlain by marine and non-marine formations. The non-marine formations are composed of fluvial and estuarine deposits of coarse sand and gravel interbedded with clay beds or lenses.

The marine formations are characterized by dark gray to black lignitic micaceous silt and clay. These micaceous silt and clay formations hydraulically separate the lower non-marine formations. The vertical hydraulic conductivity of the silty clay formations is about 1.0E-08 cm/s (3.9E-09 in./s), ranging from 1.0E-09 to 1.0E-07 cm/s (3.9E-10 to 3.9E-08 in./s). Table 4-18 lists the radionuclide specific retardation factors for the hypothetical humid site.

Surface Water. All streams in the vicinity of the disposal site discharge to a major river. The nearest surface water body is a creek, approximately 865 m (2.64E+03 ft) from the site. It flows southwest and enters into a river about 8 km (5 miles) from the site. The principal source of flow is groundwater except during periods of high rainfall.

Numerous nearby lakes are poorly drained surface depressions. Direct connection with the water table in some of the lakes results in recharge to the water table when water levels in the lakes are high, and discharge from the water table to the lake when water levels in the lakes are low. Because most lakes in the region are shallow, there is a high rate of evapotranspiration.

Groundwater. Between 60 and 70 percent of the mean annual precipitation of 117 cm (46 inches) is returned to the air through evapotranspiration. Percolation ranges from 35 to 45 cm/yr (13.8 to 17.7 inches/yr), with an average of 40 cm/yr (15.7 inches/yr). The unsaturated zone is approximately 18 m (60 ft) thick and has a porosity of about 31 percent. Laboratory measurements on sediment cores indicate that after drainage by gravity the sediments remain about 50 percent saturated. This level of saturation corresponds to a hydraulic conductivity of less than 3.5E-11 cm/s (1.4E-11 in./s). Therefore, virtually all water movement through the unsaturated zone occurs when sediments are nearly saturated.

Groundwater occurs under confined and unconfined conditions. There are two distinct water bearing zones beneath the site. The first water bearing zone is found between 18 and 76 m (55 to 250 ft) below the land surface. The second zone is between 183 and 244 m (600 to 800 ft) below the land surface. Table 4-19 presents the range of porosities and hydraulic conductivities found for these aquifers.

Table 4-18. Radionuclide retardation factors for the hypothetical humid site.

Radionuclide	Base Case	Range	Source
H-3	1	1 to 1	EPA88
C-14	1	1 to 1	EPA88
Mn-54	20,000	15,000 to 60,000	a
Fe-55	20,000	15,000 to 60,000	EPA88
Co-58	500	400 to 50,000	EPA88
Ni-59	5,000	500 to 50,000	b
Co-60	500	400 to 50,000	EPA88
Ni-63	5,000	500 to 50,000	b
Zn-65	50	20 to 500	c
Sr-90	200	50 to 5,000	NAS83
Nb-94	5,000	500 to 50,000	b
Tc-99	5	1 to 20	NAS83
I-129	1	1 to 1	NAS83
Cs-134	1,000	200 to 20,000	NAS83
Cs-137	1,000	200 to 20,000	NAS83
Ce-141	5,000	500 to 50,000	d
Ce-144	5,000	500 to 50,000	d
Pu-238	1,000	500 to 20,000	NAS83
Pu-239	1,000	500 to 20,000	NAS83
Pu-240	1,000	500 to 20,000	NAS83
Am-241	800	200 to 50,000	NAS83
Pu-241	1,000	500 to 20,000	NAS83
Cm-242	2,000	200 to 20,000	NAS83
Cm-244	2,000	200 to 20,000	NAS83

a. Assumed to be same as Fe based on chemical similarities, value from EPA88 used.

b. Assumed to be same as Zr based on chemical similarities, value from NAS83 used.

c. Assumed to be same as Pb based on chemical similarities, value from NAS83 used.

d. Assumed to be same as Th based on chemical similarities, value from NAS83 used.

Table 4-19. Aquifer properties and conductivities at the humid site.

Aquifer	Porosity	Hydraulic Conductivity (cm/s)	Gradient (m/m)
Unconfined	0.37	1.0E-05	2.5E-03
Confined	0.37	1.0E-05	2.5E-03

The groundwater has a relatively low pH (5.8) and varies between 4.5 and 7.3. Total dissolved solids values are also low (10-20 parts per million) as are specific conductivity values. Virtually all the water temperatures range from 16-22°C. The major cations are Na^+, K^+, Ca^{2+}, and Mg^{2+}, with Ca^{2+} showing the greatest variability. The major anions are Cl^-, NO_3^{2-}, and SO_4^{2-}. Table 4-20 lists the concentrations of chemical constituents critical to the lifetime of concrete structures.

The characteristics for the hypothetical humid GTCC LLW disposal site are summarized in Figure 4-27. The base case values and parameter ranges shown in the figure were used in the performance evaluation of the GTCC LLW disposal concepts and the sensitivity analysis, respectively.

Table 4-20. Concentrations of critical constituents at the arid site.

Constituent	Concentration (moles/L)		Source
	Average	Range	
Cl-	5.4e-04	2.2E-04 - 8.5E-04	RNS 1992
CO3--	3.5e-04	6.3E-05 - 6.3E-04	RNS 1992, Assumed
Mg++	3.0e-05	4.1E-06 - 5.5E-05	RNS 1992
SO4--	8.4e-05	1.9E-05 - 1.5E-04	RNS 1992
O2--	1.2e-04	6.3E-05 - 3.6E-04	Assumed

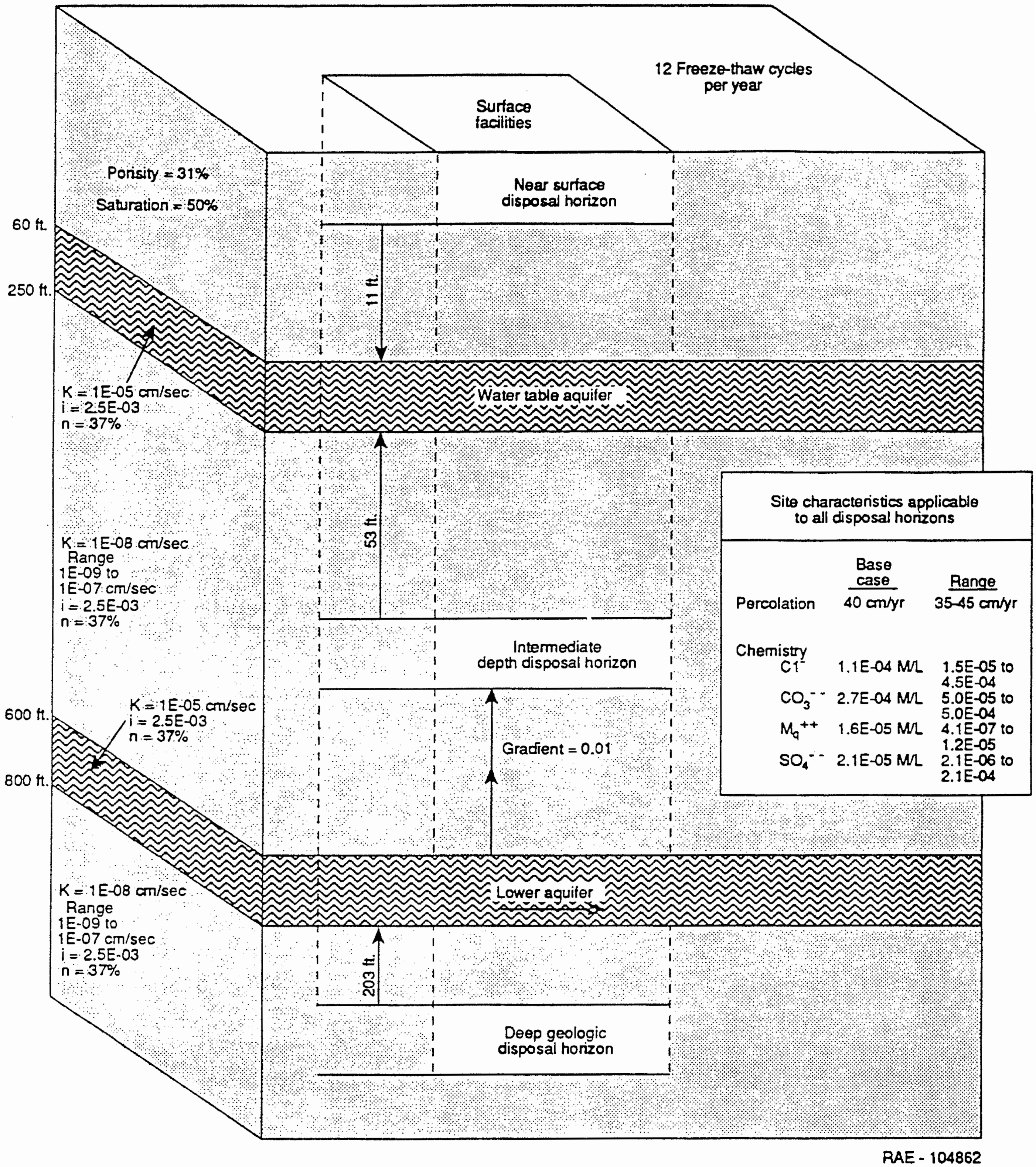


Figure 4-27. Summary of hypothetical humid site characteristics.

5. EVALUATION RESULTS

The performance of the GTCC LLW disposal concepts is a function of the performance of the waste form, the waste package, and the disposal unit, and the environmental conditions at the arid and humid sites. The technical evaluation results for these aspects are reported below for each concept and used to judge the relative effectiveness of each.

The waste packages used in all of the GTCC LLW disposal concepts and the concrete canisters or vaults used in all concepts except shallow-land disposal act as a series of barriers to the release of waste radionuclides to the environment. The performance of each disposal concept will depend, in part, on how these barriers perform, both individually and in tandem with one another. The technical evaluation results for each of these components are discussed in Section 5.1.

The performance characteristics of the waste packages and/or concrete structural components, in conjunction with the waste form and site characteristics, will determine the mechanisms and rate of radionuclides release from the waste. The results of the technical evaluation of radionuclide releases from the disposal concepts are presented in Section 5.2.

The radionuclide release rate from the GTCC LLW disposal concepts, in conjunction with site environmental characteristics, will determine the final performance characteristics of each concept. The relative performance of each disposal concept at the arid and humid site is discussed in Section 5.3.

5.1 Individual Barrier Performance

The barriers to release of radionuclides from the waste include the waste package and the concrete canisters or vaults. The performance of the high-integrity containers and the high-level-waste type containers is discussed in Section 5.1.1. The projected lifetimes of the concrete canisters and vaults are presented and discussed in Sections 5.1.2 and 5.1.3, respectively.

5.1.1 Waste Packages

Specific modeling of the performance of the high-integrity container and the high-level-waste type container was not conducted. Rather, as discussed in Section 4.2, the base-case lifetime for each container was established from regulatory requirements. For the high-integrity container, the base-case lifetime is 300 years. To judge the effect of uncertainty in this value, a range of 200 to 450 years was chosen and distributed using a log-uniform distribution (Figure 5-1). Use of a log-uniform distribution between 200 and 450 years yields an average container lifetime of 300 years. Within this range there is an equal probability a high-integrity container will fail between 200 and 300 years or between 300 and 450 years.

A mean package lifetime of 1,000 years was assumed for the high-level-waste type container. The distribution of package lifetimes was assumed to be log-uniform between 300 and 3,000 years. Based on this range and distribution, there is an equal probability that the high-level-waste type containers will fail between 300 and 1,000 years or between 1,000 and 3,000 years.

5.1.2 Concrete Canisters

Load conditions and the concentration of specific aggressive ions in the environment inside and outside the concrete barrier determine when the barrier fails. Canisters constructed as specified in Section 4.3 and subject to the range of loads and range of aggressive ion concentrations described in Sections 4.3 and 4.4, respectively, have the lifetimes shown in Tables 5-1 and 5-2. The range of lifetimes for canisters at the hypothetical arid site are listed in Table 5-1, while Table 5-2 lists the lifetimes for canisters at the hypothetical humid site.

The canister lifetimes presented in Tables 5-1 and 5-2 reflect the variations in loading conditions with canister position and the severity of the exposure conditions. The canisters subjected to the greatest loads fail first. This is illustrated by the earlier failure times noted for the bottom canisters in the mined cavity and modular concrete canister disposal concepts and the bottom-most eleven canisters in the drilled hole disposal concept. With respect to the latter concept, the loading conditions on canisters ten through twenty are identical such that these canisters exhibit the same failure characteristics.

The effect of the "high exposure" conditions (e.g., high loads and high concentrations of aggressive ions) is clearly evident in the projected canister lifetimes. The canisters subject to 20 percent greater loads, higher groundwater concentrations of aggressive ions, and order-of-magnitude diffusion rate increases, all fail at times less than 100 years, a fraction of the lifetimes found under nominal or base-case exposure conditions. The accelerated rate of concrete deterioration due to chemical attack undermines the ability of the structures to withstand the increased loads placed upon them.

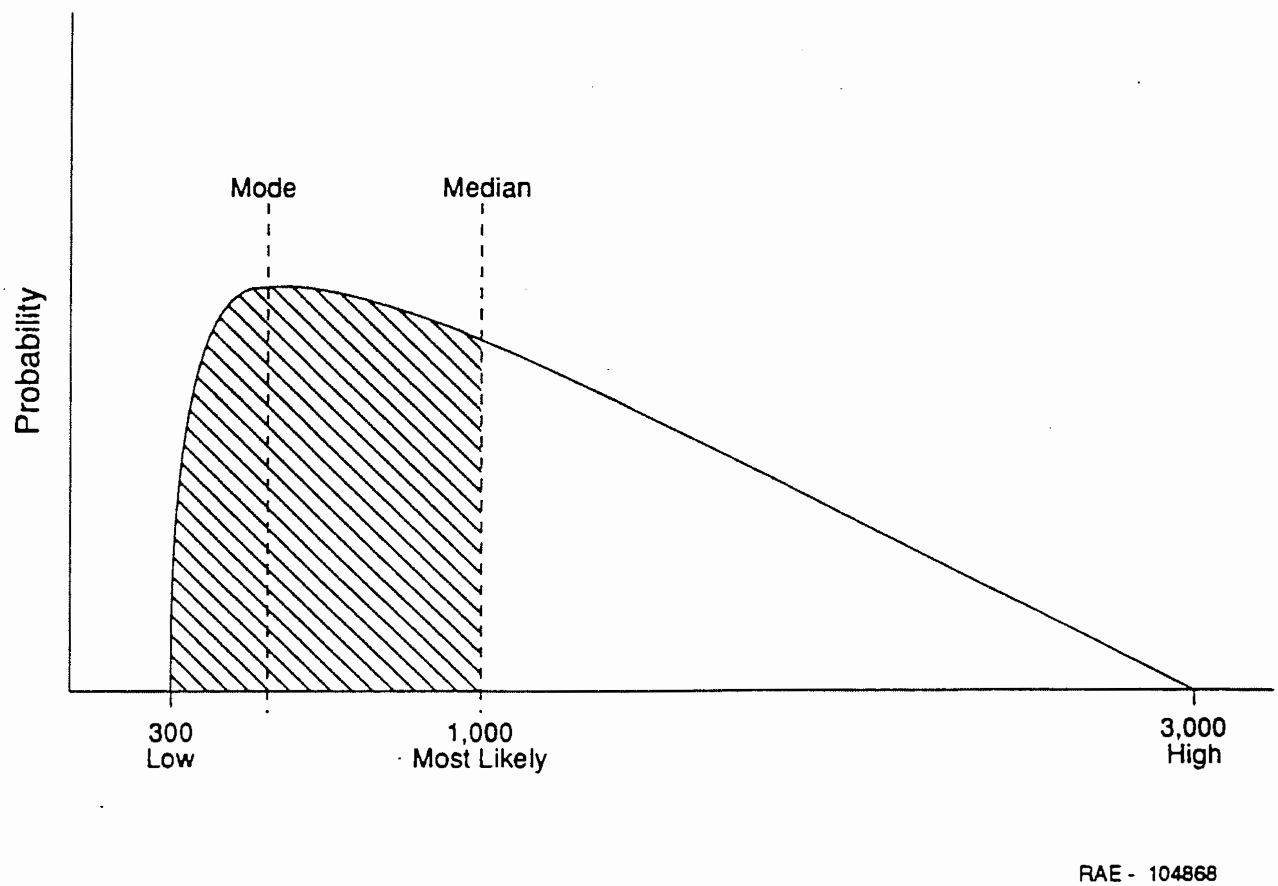


Figure 5-1. Log uniform distribution for failure of a high-level waste type container.

Table 5-1. Range of concrete canister lifetimes at the hypothetical arid site.

Disposal concept	Canister location	Base-case (years)	High exposure case (years)
Near-surface			
Modular concrete canister	Top	450	30
	Bottom	250	10
Intermediate-depth			
Drilled hole	Top	1,300	100
	Lower	850	50
Mined cavity	Top	950	70
	Bottom	650	50
Deep geologic			
Drilled hole	Top	1,300	100
	Lower	850	50
Mined cavity	Top	950	70
	Bottom	650	50

Table 5-2. Range of concrete canister lifetimes at the hypothetical humid site.

Disposal concept	Canister location	Base-case (years)	High exposure case (years)
Near-surface			
Modular concrete canister	Top	1,500	20
	Bottom	800	10
Intermediate-depth			
Drilled hole	Top	2,200	70
	Lower	2,200	50
Mined cavity	Top	2,200	50
	Bottom	2,200	30
Deep geologic			
Drilled hole	Top	2,200	70
	Lower	2,200	50
Mined cavity	Top	2,200	50
	Bottom	2,100	30

Canister lifetimes observed at the humid site are typically greater than those seen at the arid site for the base-case exposure conditions. Lifetimes are similar between the two sites when the canisters are subjected to the high exposure conditions. The greater canister lifetimes noted for the modular concrete concept under base-case conditions is due to the fact that concentrations of aggressive ions in the groundwater at the humid site are lower than those at the arid site. Lower ion concentrations translate into slower rates of concrete deterioration; extending the time over which the structures can bear design loads.

The longer canister lifetimes noted at the humid site for the mined cavity and drilled hole disposal concepts are a result of the less aggressive chemical conditions at the site and differences in loading conditions between the humid and arid sites. The saturated strata in which the canisters are placed at the humid site for the mined cavity and drilled hole concepts have the effect of lowering the loads the canisters must bear. Consequently, the time over which concrete deterioration can occur before undermining the canisters' load-bearing capabilities is lengthened.

As discussed in Section 3, the canister lifetime projections for the base-case and high exposure conditions were used to construct lifetime distributions for the concrete canisters. Based on engineering judgment and familiarity with the concrete degradation models, a low value, a most likely value or mode, and a high value for the canister lifetime are designated and a distribution is assigned for each disposal concept. The low end of the range represents the failure time of the canisters under the high exposure conditions, while the high end of the range represents the maximum lifetime expected for the canister under the base-case conditions.

A triangular distribution was chosen to represent the variability of canister lifetime within the range of lifetimes (Figure 5-2). The low and high values, and the mode are used to define the median of the distribution, the point of the distribution where there is an equal number of values on either side.

The low and high values, and the modes for each of the disposal concepts which employs canisters at the two hypothetical sites are provided in Table 5-3. Two of the triangular distributions based on these data are shown in Figures 5-3 and 5-4. In each of these examples, there is an equal probability that a given canister will have a lifetime that falls within the shaded area as there is that its lifetime will fall within the unshaded area.

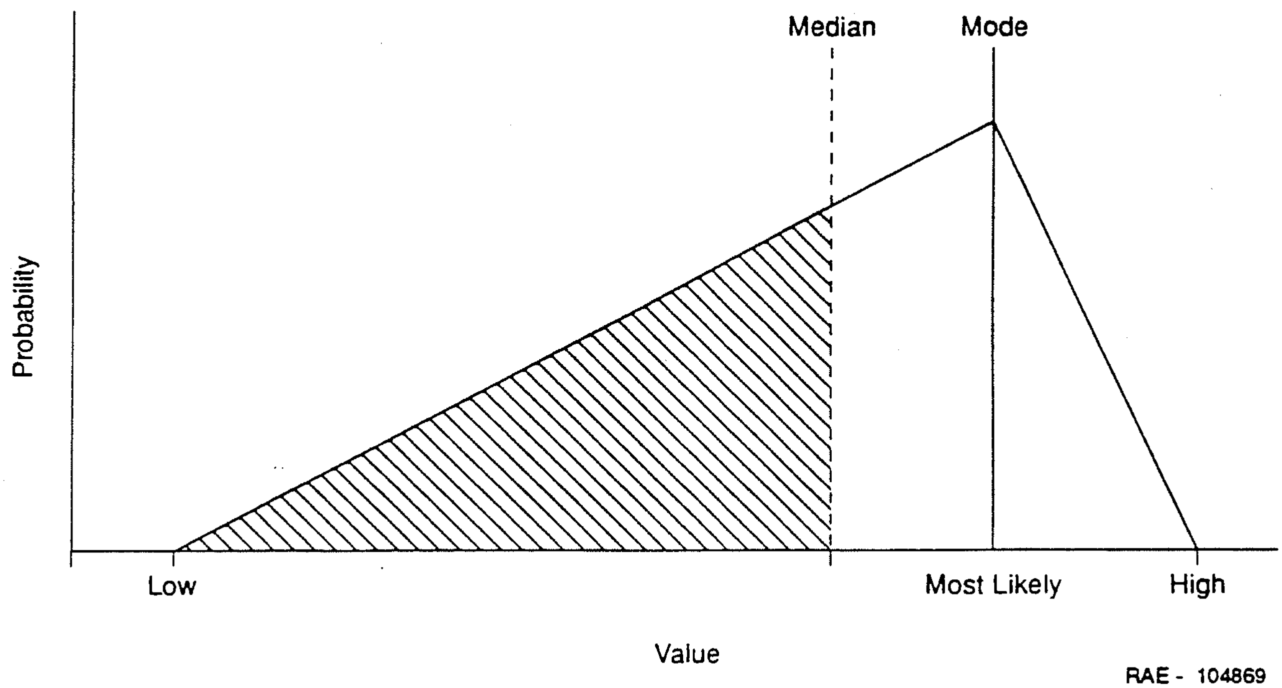


Figure 5-2. Example of triangular distribution.

Table 5-3. Distribution of concrete canister lifetimes in years at the hypothetical site.

Disposal concept	Low value	Mode	High value
Arid site			
Near-surface			
Modular concrete canister	10	250	450
Intermediate-depth			
Drilled hole	50	850	1,300
Mined cavity	50	650	950
Deep geologic			
Drilled hole	50	850	1,300
Mined cavity	50	650	950
Humid site			
Near-surface			
Modular concrete canister	10	820	1,500
Intermediate-depth			
Drilled hole	40	2,200	2,200
Mined cavity	30	2,100	2,200
Deep geologic			
Drilled hole	40	2,200	2,200
Mined cavity	30	2,100	2,200

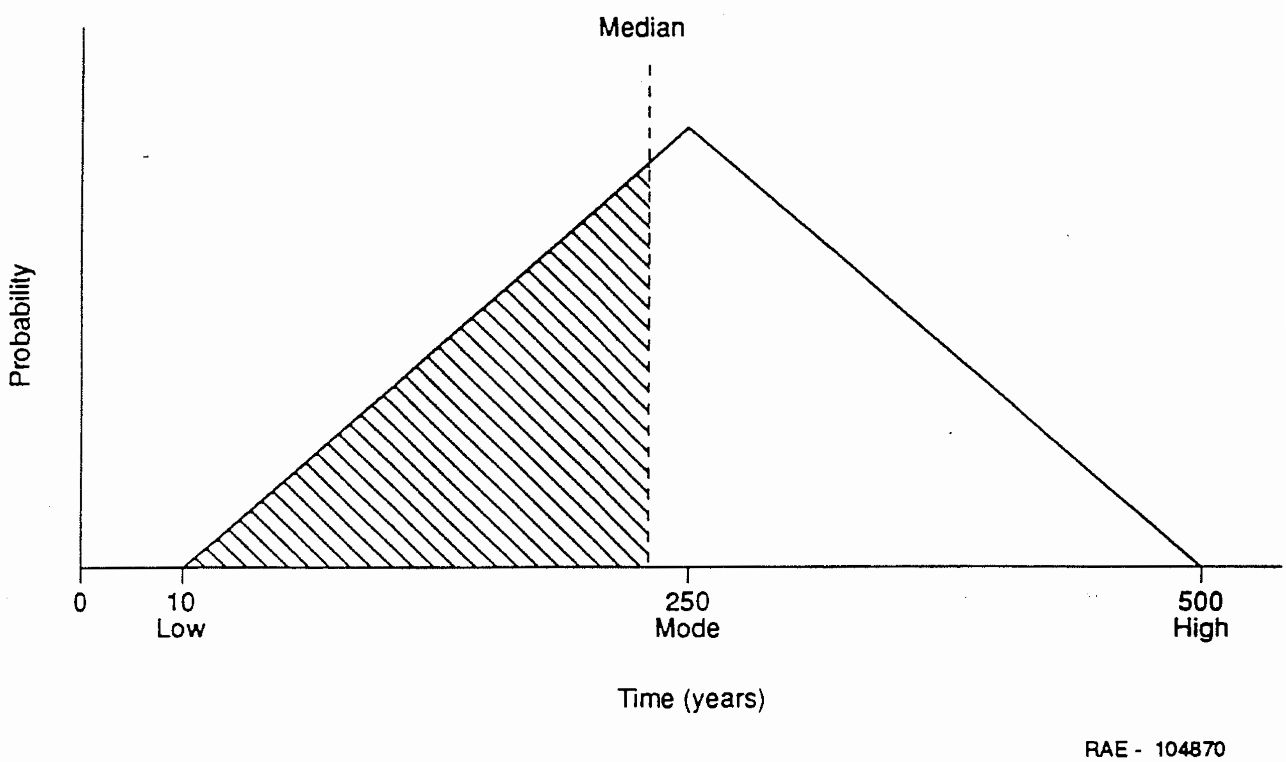


Figure 5-3. Arid near-surface modular concrete canister -- distribution of canister lifetimes.

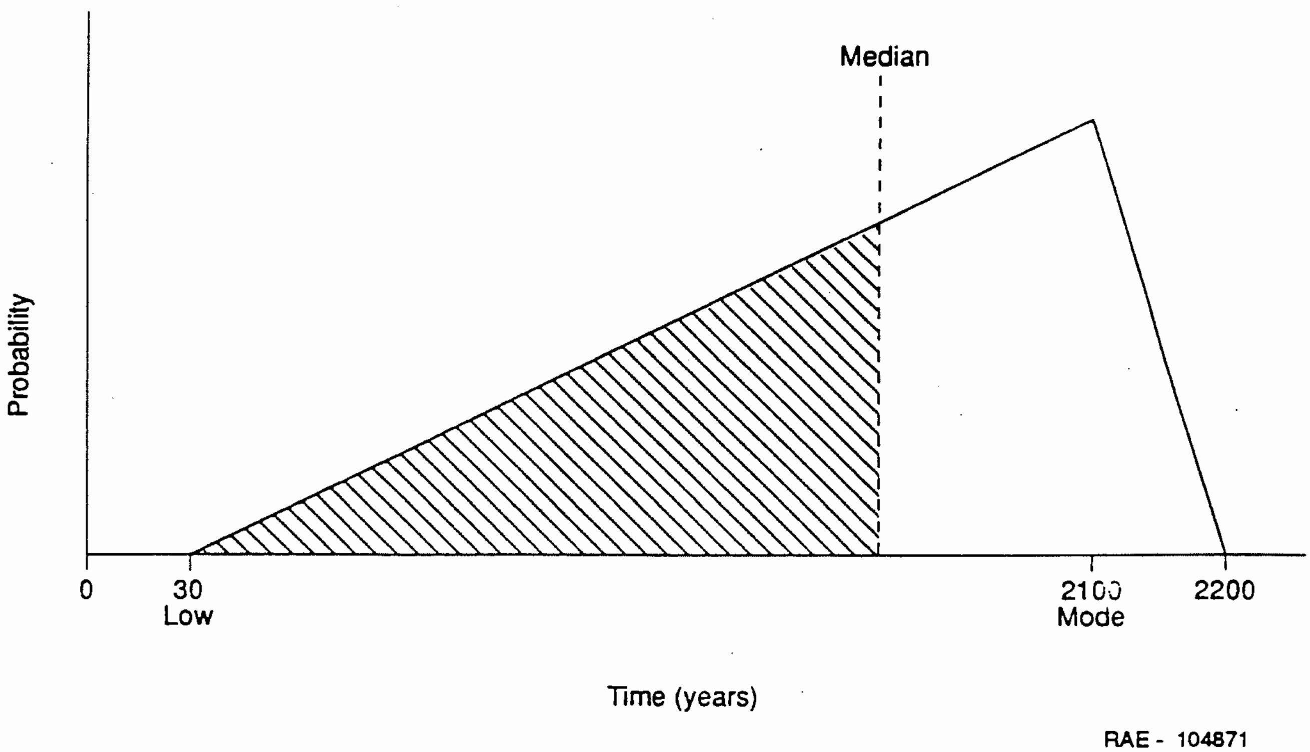


Figure 5-4. Humid deep geologic mined cavity -- distribution of canister lifetime.

5.1.3 Concrete Vaults

Concrete vaults constructed as specified in Section 4.3 and subject to the range of loads and aggressive ion concentrations described in Sections 4.3 and 4.4, respectively, have the lifetimes shown in Tables 5-4 and 5-5. The range of lifetimes for vaults at the hypothetical arid site are listed in Table 5-4, while Table 5-5 lists the lifetimes for concrete vaults at the hypothetical humid site.

The projected lifetimes for the aboveground, belowground, and earth-mounded concrete vaults generally exceed the projected canister lifetimes by a factor of two or more. These results are indicative of the more robust concrete members, relative to the loading conditions, used in the design of the concrete vaults.

Projected lifetimes for the belowground and earth-mounded vaults are the same at each site because design and loading conditions are identical for these concepts. Failure of the belowground and earth-mounded vaults at the arid site is projected to occur at times much earlier than the failure time for the aboveground vault. This is due to the fact that chemical attack of the aboveground vaults is modeled to occur on the inside of the vault roof and walls only, whereas deterioration of these members in the other vaults occurs on the interior and exterior faces of these members. The addition of freeze-thaw attack at the humid site minimizes the effect of differences in rates of chemical attack between the various vault concepts.

The projected lifetimes of all of the vaults are much shorter for high exposure conditions than for base-case conditions. Estimated lifetimes for the belowground and earth-mounded vaults are substantially longer at the humid site than at the arid site due to the lower groundwater concentrations of aggressive ions.

The projected lifetimes of the aboveground vault at the arid and humid sites are similar for the base case conditions, despite the fact that the humid site is characterized by less aggressive chemical exposure conditions. However, deterioration of the concrete vaults at the humid site due to freeze-thaw cycling effectively negates the benefits of the less aggressive chemical environment.

Vault lifetime projections for the base-case and high exposure conditions were used to construct lifetime distributions for the concrete vaults. Consistent with the approach taken in modeling canister lifetime, a low value, a mode, and a high value for vault lifetime are designated and a distribution is

Table 5-4. Range of concrete vault lifetimes at the hypothetical arid site.

Disposal concept	Base-case (years)	High exposure case (years)
Belowground	1,850	109
Aboveground	6,020	430
Earth-mounded	1,850	109

Table 5-5. Range of concrete vault lifetimes at the hypothetical humid site.

Disposal concept	Base-case (years)	High exposure case (years)
Belowground	6,800	80
Aboveground	6,100	200
Earth-mounded	6,800	80

assigned for each disposal concept. The low end of the range represents the failure time of the vault under high exposure conditions; the high value represents the maximum lifetime projected for the vault under the base-case conditions. The distribution of vault lifetimes is described using a triangular distribution (shown in Figure 5-2). The low and high values, and the mode are used to define the median of the distribution.

The low and high values, and the modes for each of the disposal concepts which employs vaults at the two hypothetical sites are provided in Table 5-6. Figure 5-5 is an example the triangular distribution for the arid site belowground vault. Distributions for the vaults at both the arid and humid sites have this same shape. There is an equal probability that the vault lifetime will a) fall between the low value and the calculated median and b) fall between the median and the high value.

5.2 Waste Form Release Rates

The rate at which radionuclides are released from GTCC LLW is dependent upon the waste-form and the condition of the barriers discussed above (i.e. the waste package and the concrete canister or vault). When each of these barriers is intact, no releases from the waste can occur; inventory reduction occurs entirely due to radioactive decay. If the waste package fails prior to failure of the concrete canister or vault, radionuclide releases may occur due to diffusion. Following the failure of the waste package and the concrete canister or vault, water percolating through the disposal horizon will come in direct contact with the waste and advective releases may begin.

While the condition of the waste package and concrete canister or vault will determine what release mechanisms may occur, the rate of release will also depend upon the waste-form. Radionuclides will be released from process waste, contaminated equipment and materials, and sealed sources (following failure of the stainless steel jacket) as permitted by the condition of the waste containers and concrete barriers. Releases of radionuclides from activated metals may be limited by the rate at which the metal components undergo corrosion. In the event that the corrosion rate is less than rates of release due to diffusion and/or advection, the corrosion based release rate will apply.

Releases of radionuclides from the shallow-land disposal concept will occur due to advection only for process waste, contaminated equipment and materials, and sealed sources (following failure of the stainless steel jacket). The corrosion rate for the activated metals may limit releases from the facility.

Table 5-6. Distribution of concrete vault lifetimes in years at the hypothetical site.

Disposal concept	Low value	Mode	High value
Arid site			
Belowground	100	1,850	1,850
Aboveground	430	6,000	6,000
Earth-mounded	100	1,850	1,850
Humid site			
Belowground	80	6,800	6,800
Aboveground	180	6,100	6,100
Earth-mounded	80	6,800	6,800

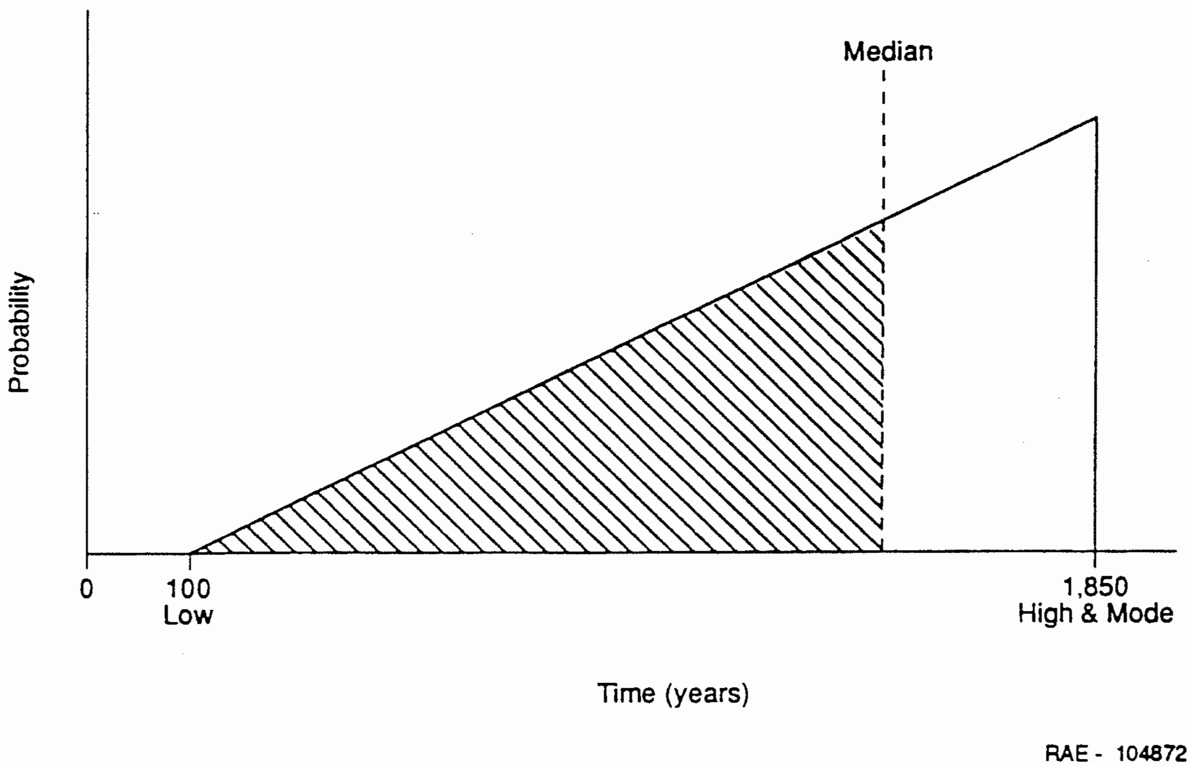


Figure 5-5. Arid belowground vault -- distribution of vault lifetimes.

The results of the radionuclide release calculations for the various disposal concepts are presented in the following subsections. Results of diffusive leach modeling are given in Section 5.2.1, while the results of the advective leach calculations are provided in Section 5.2.2.

5.2.1 Diffusive Releases

As discussed in Section 3, average diffusive release rates were calculated for each disposal concept based on the projected lifetimes of the waste package and concrete canister or vault. The diffusive release period used in these calculations extended from the minimum lifetime of the waste package to the maximum lifetime of the canister or vault. These diffusive periods are listed for the various disposal concepts at the arid and humid sites in Tables 5-7 and 5-8, respectively. The annual release rate due to diffusion is calculated using the methodology described in Section 3 for the a range of diffusion coefficients for each radionuclide.

The annual fractional release rates due to diffusion for the GTCC LLW disposal concepts at the arid site are provided in Tables 5-9 through 5-15. Table 5-9 presents the diffusion rates applicable to the belowground and earth-mounded concrete vault concepts. Diffusive release rates for aboveground vault and the modular concrete canister concepts are listed in tables 5-10 and 5-11, respectively. Release rates for the intermediate-depth and deep geologic drilled hole concepts using high integrity containers are shown in Table 5-12; results for these concepts using high-level-waste type containers are presented in Table 5-13. Annual diffusive release rates for high-integrity containers and high-level-waste type containers in the mined cavity concept are shown in Tables 5-14 and 5-15, respectively.

The calculated annual diffusive release rates for the GTCC LLW disposal concepts at the humid site are listed in Tables 5-16 through 5-22. Results for the belowground and earth-mounded concrete vault concepts are given in Table 5-16. Release rates for the Above Ground Vault and the Modular Concrete Canister concepts are presented in tables 5-17 and 5-18, respectively. The annual diffusive release rates for the intermediate depth and deep geologic drilled holes concepts using high-integrity containers are shown in Table 5-19, rates for these concepts using high-level-waste type containers are presented in Table 5-20. The annual diffusive release rates for high-integrity containers and high-level-waste type containers in the mined cavity concept are shown in Tables 5-21 and 5-22, respectively.

The diffusive release rates in Tables 5-9 through 5-22 are labeled as either "low" or "high." Rates labeled as low are the rates of release corresponding to the high distribution coefficients for the concrete

Table 5-7. Diffusive release periods at the hypothetical arid site.

	Diffusive release period	
Disposal concept	Start	End
Near-Surface		
Shallow-land disposal	None	
Belowground vault		
High-integrity container	200	1,850
Aboveground vault		
High-integrity container	200	6,000
Earth-mounded vault		
High-integrity container	200	1,850
Modular concrete canister		
High-integrity container	200	450
Intermediate-depth		
Drilled hole		
High-integrity container	200	1,300
High-level-waste type container	300	1,300
Mined cavity		
High-integrity container	200	950
High-level-waste type container	300	950
Deep geologic		
Drilled hole		
High-integrity container	200	1,300
High-level-waste type container	300	1,300
Mined cavity		
High-integrity container	200	950
High-level-waste type container	300	950

Table 5-8. Diffusive release periods at the hypothetical humid site.

Disposal concept	Diffusive release period Start	End
Near-Surface		
Shallow-land disposal	None	
Belowground vault		
High-integrity container	200	6,800
Aboveground vault		
High-integrity container	200	6,100
Earth-mounded vault		
High-integrity container	200	6,800
Modular concrete canister		
High-integrity container	200	1,500
Intermediate-depth		
Drilled hole		
High-integrity container	200	2,200
High-level-waste type container	300	2,200
Mined cavity		
High-integrity container	200	2,200
High-level-waste type container	300	2,200
Deep geologic		
Drilled hole		
High-integrity container	200	2,200
High-level-waste type container	300	2,200
Mined cavity		
High-integrity container	200	2,200
High-level-waste type container	300	2,200

Table 5-9. Arid site annual fractional diffusive release rates for belowground and earth-mounded concrete vaults.

	Low	High
Am-241	1.50E-08	2.88E-05
C-14	2.88E-05	4.01E-04
Cs-134	4.36E-23	4.01E-04
Cs-137	4.36E-23	4.01E-04
I-129	3.97E-04	4.01E-04
Nb-94	2.76E-07	2.46E-04
Ni-59	2.09E-05	7.41E-05
Ni-63	2.09E-05	7.41E-05
Pu-238	3.05E-09	2.88E-05
Pu-239	3.05E-09	2.88E-05
Pu-240	3.05E-09	2.88E-05
Pu-241	3.05E-09	2.88E-05
Sr-90	3.77E-14	4.01E-04
Tc-99	2.14E-06	4.01E-04

Table 5-10. Arid site annual fractional diffusive release rates for aboveground vault.

	Low	High
Am-241	4.57E-06	6.13E-05
C-14	6.13E-05	1.77E-04
Cs-134	4.66E-09	1.77E-04
Cs-137	4.66E-09	1.77E-04
I-129	1.74E-04	1.77E-04
Nb-94	1.05E-05	1.58E-04
Ni-59	5.29E-05	9.78E-05
Ni-63	5.29E-05	9.78E-05
Pu-238	3.02E-06	6.13E-05
Pu-239	3.02E-06	6.13E-05
Pu-240	3.02E-06	6.13E-05
Pu-241	3.02E-06	6.13E-05
Sr-90	2.37E-07	1.77E-04
Tc-99	2.08E-05	1.77E-04

Table 5-11. Arid site annual fractional diffusive release rates for modular concrete canister.

	Low	High
Am-241	7.71E-06	7.80E-04
C-14	7.80E-04	3.93E-03
Co-58	6.24E-04	1.52E-03
Co-60	6.24E-04	1.52E-03
Fe-55	6.24E-04	1.52E-03
H-3	3.93E-03	3.93E-03
I-129	3.91E-03	3.93E-03
Mn-54	3.20E-06	3.93E-03
Nb-94	4.08E-05	3.26E-03
Ni-59	6.24E-04	1.52E-03
Ni-63	6.24E-04	1.52E-03
Sr-90	8.24E-09	3.93E-03
Tc-99	1.41E-04	3.93E-03

Table 5-12. Arid site annual fractional diffusive release rates for drilled holes using high-integrity containers.

	Low	High
Am-241	8.37E-05	6.50E-04
C-14	6.50E-04	2.91E-03
Ce-141	4.28E-07	2.91E-03
Ce-144	4.28E-07	2.91E-03
Cm-241	8.37E-05	6.50E-04
Cm-244	8.37E-05	6.50E-04
Co-58	5.92E-04	8.15E-04
Co-60	5.92E-04	8.15E-04
Cs-134	4.28E-07	2.91E-03
Cs-137	4.28E-07	2.91E-03
Fe-55	5.92E-04	8.15E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	5.98E-05	2.91E-03
Nb-94	1.67E-04	1.45E-03
Ni-59	5.92E-04	8.15E-04
Ni-63	5.92E-04	8.15E-04
Pu-238	5.98E-05	6.50E-04
Pu-239	5.98E-05	6.50E-04
Pu-240	5.98E-05	6.50E-04
Pu-241	5.98E-05	6.50E-04
Sr-90	8.12E-06	2.91E-03
Tc-99	2.94E-04	2.91E-03
Zn-65	5.98E-05	2.91E-03

Table 5-13. Arid site annual fractional diffusive release rates for drilled holes using high-level-waste containers.

	Low	High
Am-241	7.89E-05	6.78E-04
C-14	6.78E-04	2.91E-03
Ce-141	2.87E-07	2.91E-03
Ce-144	2.87E-07	2.91E-03
Cm-241	7.89E-05	6.78E-04
Cm-244	7.89E-05	6.78E-04
Co-58	6.13E-04	8.74E-04
Co-60	6.13E-04	8.74E-04
Cs-134	2.87E-07	2.91E-03
Cs-137	2.87E-07	2.91E-03
Fe-55	6.13E-04	8.74E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	5.54E-05	2.91E-03
Nb-94	1.63E-04	1.45E-03
Ni-59	6.13E-04	8.74E-04
Ni-63	6.13E-04	8.74E-04
Pu-238	5.54E-05	6.78E-04
Pu-239	5.54E-05	6.78E-04
Pu-240	5.54E-05	6.78E-04
Pu-241	5.54E-05	6.78E-04
Sr-90	6.70E-06	2.91E-03
Tc-99	2.93E-04	2.91E-03
Zn-65	5.54E-05	2.91E-03

Table 5-14. Arid site annual fractional diffusive release rates for mined cavity using high-integrity containers.

	Low	High
Am-241	6.01E-05	7.63E-04
C-14	7.63E-04	2.91E-03
Ce-141	5.02E-08	2.91E-03
Ce-144	5.02E-08	2.91E-03
Cm-241	6.01E-05	7.63E-04
Cm-244	6.01E-05	7.63E-04
Co-58	6.72E-04	1.08E-03
Co-60	6.72E-04	1.08E-03
Cs-134	5.02E-08	2.91E-03
Cs-137	5.02E-08	2.91E-03
Fe-55	6.72E-04	1.08E-03
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	3.93E-05	2.91E-03
Nb-94	1.41E-04	1.45E-03
Ni-59	6.72E-04	1.08E-03
Ni-63	6.72E-04	1.08E-03
Pu-238	3.93E-05	7.63E-04
Pu-239	3.93E-05	7.63E-04
Pu-240	3.93E-05	7.63E-04
Pu-241	3.93E-05	7.63E-04
Sr-90	2.89E-06	2.91E-03
Tc-99	2.80E-04	2.91E-03
Zn-65	3.93E-05	2.91E-03

Table 5-15. Arid site annual fractional diffusive release rates for mined cavity using high-level-waste containers.

	Low	High
Am-241	5.13E-05	7.91E-04
C-14	7.91E-04	2.91E-03
Ce-141	1.92E-08	2.91E-03
Ce-144	1.92E-08	2.91E-03
Cm-241	5.13E-05	7.91E-04
Cm-244	5.13E-05	7.91E-04
Co-58	6.89E-04	1.17E-03
Co-60	6.89E-04	1.17E-03
Cs-134	1.92E-08	2.91E-03
Cs-137	1.92E-08	2.91E-03
Fe-55	6.89E-04	1.17E-03
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	3.23E-05	2.91E-03
Nb-94	1.29E-04	1.55E-03
Ni-59	6.89E-04	1.17E-03
Ni-63	6.89E-04	1.17E-03
Pu-238	3.23E-05	7.91E-04
Pu-239	3.23E-05	7.91E-04
Pu-240	3.23E-05	7.91E-04
Pu-241	3.23E-05	7.91E-04
Sr-90	1.82E-06	2.91E-03
Tc-99	2.68E-04	2.91E-03
Zn-65	3.23E-05	2.91E-03

Table 5-16. Humid site annual fractional diffusive release rates for belowground and earth-mounded concrete vaults.

	Low	High
Am-241	1.83E-06	4.60E-05
C-14	4.60E-05	1.50E-04
Cs-134	8.71E-11	1.50E-04
Cs-137	8.71E-11	1.50E-04
I-129	1.50E-04	1.50E-04
Nb-94	5.45E-06	1.36E-04
Ni-59	3.88E-05	7.79E-05
Ni-63	3.88E-05	7.79E-05
Pu-238	1.05E-06	4.60E-05
Pu-239	1.05E-06	4.60E-05
Pu-240	1.05E-06	4.60E-05
Pu-241	1.05E-06	4.60E-05
Sr-90	2.97E-08	1.50E-04
Tc-99	1.28E-05	1.50E-04

Table 5-17. Humid site annual fractional diffusive release rates for aboveground vault.

	Low	High
Am-241	4.62E-06	6.13E-05
C-14	6.13E-05	1.77E-04
Cs-134	5.07E-09	1.77E-04
Cs-137	5.07E-09	1.77E-04
I-129	1.74E-04	1.77E-04
Nb-94	1.06E-05	1.56E-04
Ni-59	5.29E-05	9.72E-05
Ni-63	5.29E-05	9.72E-05
Pu-238	3.07E-06	6.13E-05
Pu-239	3.07E-06	6.13E-05
Pu-240	3.07E-06	6.13E-05
Pu-241	3.07E-06	6.13E-05
Sr-90	2.47E-07	1.77E-04
Tc-99	2.10E-05	1.77E-04

Table 5-18. Humid site annual fractional diffusive release rates for modular concrete canister.

	Low	High
Am-241	9.03E-05	6.05E-04
C-14	6.05E-04	2.91E-03
Ce-141	7.35E-07	2.91E-03
Ce-144	7.35E-07	2.91E-03
Cm-241	9.03E-05	6.05E-04
Cm-244	9.03E-05	6.05E-04
Co-58	5.57E-04	7.29E-04
Co-60	5.57E-04	7.29E-04
Cs-134	7.35E-07	2.91E-03
Cs-137	7.35E-07	2.91E-03
Fe-55	5.57E-04	7.29E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	6.61E-05	2.91E-03
Nb-94	1.73E-04	1.45E-03
Ni-59	5.57E-04	7.29E-04
Ni-63	5.57E-04	7.29E-04
Pu-238	6.61E-05	6.05E-04
Pu-239	6.61E-05	6.05E-04
Pu-240	6.61E-05	6.05E-04
Pu-241	6.61E-05	6.05E-04
Sr-90	1.05E-05	2.91E-03
Tc-99	2.93E-04	2.91E-03
Zn-65	6.61E-05	2.91E-03

Table 5-19. Humid site annual fractional diffusive release rates for drilled holes using high-integrity containers.

	Low	High
Am-241	1.06E-04	4.55E-04
C-14	4.55E-04	2.91E-03
Ce-141	2.62E-06	2.91E-03
Ce-144	2.62E-06	2.91E-03
Cm-241	1.06E-04	4.55E-04
Cm-244	1.06E-04	4.55E-04
Co-58	4.34E-04	4.95E-04
Co-60	4.34E-04	4.95E-04
Cs-134	2.62E-06	2.91E-03
Cs-137	2.62E-06	2.91E-03
Fe-55	4.34E-04	4.95E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	8.15E-05	2.91E-03
Nb-94	1.79E-04	1.45E-03
Ni-59	4.34E-04	4.95E-04
Ni-63	4.34E-04	4.95E-04
Pu-238	8.15E-05	4.55E-04
Pu-239	8.15E-05	4.55E-04
Pu-240	8.15E-05	4.55E-04
Pu-241	8.15E-05	4.55E-04
Sr-90	1.91E-05	2.91E-03
Tc-99	2.73E-04	2.91E-03
Zn-65	8.15E-05	2.91E-03

Table 5-20. Humid site annual fractional diffusive release rates for drilled holes using high-level-waste type containers.

	Low	High
Am-241	1.04E-04	4.73E-04
C-14	4.73E-04	2.91E-03
Ce-141	2.31E-06	2.91E-03
Ce-144	2.31E-06	2.91E-03
Cm-241	1.04E-04	4.73E-04
Cm-244	1.04E-04	4.73E-04
Co-58	4.49E-04	5.19E-04
Co-60	4.49E-04	5.19E-04
Cs-134	2.31E-06	2.91E-03
Cs-137	2.31E-06	2.91E-03
Fe-55	4.49E-04	5.19E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	8.00E-05	2.91E-03
Nb-94	1.79E-04	1.45E-03
Ni-59	4.49E-04	5.19E-04
Ni-63	4.49E-04	5.19E-04
Pu-238	8.00E-05	4.73E-04
Pu-239	8.00E-05	4.73E-04
Pu-240	8.00E-05	4.73E-04
Pu-241	8.00E-05	4.73E-04
Sr-90	1.80E-05	2.91E-03
Tc-99	2.77E-04	2.91E-03
Zn-65	8.00E-05	2.91E-03

Table 5-21. Humid site annual fractional diffusive release rates for mined cavity using high-integrity containers.

	Low	High
Am-241	1.06E-04	4.55E-04
C-14	4.55E-04	2.91E-03
Ce-141	2.62E-06	2.91E-03
Ce-144	2.62E-06	2.91E-03
Cm-241	1.06E-04	4.55E-04
Cm-244	1.06E-04	4.55E-04
Co-58	4.34E-04	4.95E-04
Co-60	4.34E-04	4.95E-04
Cs-134	2.62E-06	2.91E-03
Cs-137	2.62E-06	2.91E-03
Fe-55	4.34E-04	4.95E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	8.15E-05	2.91E-03
Nb-94	1.79E-04	1.45E-03
Ni-59	4.34E-04	4.95E-04
Ni-63	4.34E-04	4.95E-04
Pu-238	8.15E-05	4.55E-04
Pu-239	8.15E-05	4.55E-04
Pu-240	8.15E-05	4.55E-04
Pu-241	8.15E-05	4.55E-04
Sr-90	1.91E-05	2.91E-03
Tc-99	2.73E-04	2.91E-03
Zn-65	8.15E-05	2.91E-03

Table 5-22. Humid site annual fractional diffusive release rates for mined cavity using high-level-waste type containers.

	Low	High
Am-241	1.04E-04	4.73E-04
C-14	4.73E-04	2.91E-03
Ce-141	2.31E-06	2.91E-03
Ce-144	2.31E-06	2.91E-03
Cm-241	1.04E-04	4.73E-04
Cm-244	1.04E-04	4.73E-04
Co-58	4.49E-04	5.19E-04
Co-60	4.49E-04	5.19E-04
Cs-134	2.31E-06	2.91E-03
Cs-137	2.31E-06	2.91E-03
Fe-55	4.49E-04	5.19E-04
H-3	2.91E-03	2.91E-03
I-129	2.85E-03	2.91E-03
Mn-54	8.00E-05	2.91E-03
Nb-94	1.79E-04	1.45E-03
Ni-59	4.49E-04	5.19E-04
Ni-63	4.49E-04	5.19E-04
Pu-238	8.00E-05	4.73E-04
Pu-239	8.00E-05	4.73E-04
Pu-240	8.00E-05	4.73E-04
Pu-241	8.00E-05	4.73E-04
Sr-90	1.80E-05	2.91E-03
Tc-99	2.77E-04	2.91E-03
Zn-65	8.00E-05	2.91E-03

and grouted waste used in the analysis. The rates labeled as high are the rates of release corresponding to the low distribution coefficients for the concrete and grouted waste. These distribution coefficients were provided in Section 3.

5.2.2 Advective Releases

Advective releases may occur after the inner (waste package) and outer (concrete) barriers both fail. This condition can exist at any time after the minimum lifetime of the two barriers, year 200 for the high-integrity containers and year 300 for the high-level-waste type containers. The advective release rates, like the diffusive release rates, depend on the retardation factors for the various radionuclides. In addition, the advective release rate also depends on the percolation rate. This dependency is important at the humid site where the cover system reduces the percolation rate for the covered near surface concepts by 38 cm/yr (15 inches/yr) or 95 percent for a period of 1,000 years after site closure. While the same percentage reduction occurs at the arid site, the magnitude of the reduction is negligible in terms of the advective releases. The cover system is not assumed to influence rates of water percolation through the waste at either site for the intermediate-depth or deep geologic disposal concepts.

The calculated annual fractional advective release rates for the GTCC LLW disposal concepts at the arid site are provided in Tables 5-23 and 5-24. Release rates for all disposal concepts which employ vaults are shown in Table 5-23. Advective release rates for all of the concepts which employ concrete canisters are given in Table 5-24.

The calculated annual fractional advective release rates for the GTCC LLW disposal concepts are given for the humid site in Tables 5-25 and 5-26. The advective release rates for the concepts using vaults are given in Table 5-25. The release rates given for the low percolation case in this table do not apply to the aboveground vault concept. The annual advective release rates for the modular concrete canister concept and all intermediate-depth and deep geologic concepts are given in Table 5-26. The advective release rates given for the low percolation case apply only to the near-surface modular concrete canister disposal concept.

5.3 Disposal Concept Performance

To evaluate the containment performance of the 13 GTCC LLW disposal concepts for each of the four waste categories (activated metals, process waste, contaminated equipment and material, and sealed

Table 5-23. Arid site annual fractional advective release rates for concepts using vaults.

	Low	High
Am-241	7.05E-06	5.10E-05
C-14	5.10E-05	3.75E-04
Ce-141	5.88E-07	3.75E-04
Ce-144	5.88E-07	3.75E-04
Cm-241	7.05E-06	5.10E-05
Cm-244	7.05E-06	5.10E-05
Co-58	2.87E-05	8.98E-05
Co-60	2.87E-05	8.98E-05
Cs-134	1.15E-06	3.75E-04
Cs-137	1.15E-06	3.75E-04
Fe-55	3.56E-05	8.98E-05
H-3	3.75E-04	3.75E-04
I-129	3.70E-04	3.75E-04
Mn-54	3.65E-06	3.75E-04
Nb-94	1.14E-05	2.30E-04
Ni-59	4.34E-05	8.98E-05
Ni-63	4.34E-05	8.98E-05
Pu-238	5.80E-06	5.10E-05
Pu-239	5.80E-06	5.10E-05
Pu-240	5.80E-06	5.10E-05
Pu-241	5.80E-06	5.10E-05
Sr-90	2.44E-06	3.75E-04
Tc-99	1.87E-05	3.75E-04
Zn-65	4.48E-06	3.75E-04

Table 5-24. Arid site annual fractional advective release rates for concepts using concrete canisters.

	Low	High
Am-241	1.53E-05	1.11E-04
C-14	1.11E-04	8.15E-04
Ce-141	1.28E-06	8.15E-04
Ce-144	1.28E-06	8.15E-04
Cm-241	1.53E-05	1.11E-04
Cm-244	1.53E-05	1.11E-04
Co-58	6.23E-05	1.95E-04
Co-60	6.23E-05	1.95E-04
Cs-134	2.51E-06	8.15E-04
Cs-137	2.51E-06	8.15E-04
Fe-55	7.74E-05	1.95E-04
H-3	8.15E-04	8.15E-04
I-129	8.05E-04	8.15E-04
Mn-54	7.93E-06	8.15E-04
Nb-94	2.49E-05	5.00E-04
Ni-59	9.45E-05	1.95E-04
Ni-63	9.45E-05	1.95E-04
Pu-238	1.26E-05	1.11E-04
Pu-239	1.26E-05	1.11E-04
Pu-240	1.26E-05	1.11E-04
Pu-241	1.26E-05	1.11E-04
Sr-90	5.31E-06	8.15E-04
Tc-99	4.06E-05	8.15E-04
Zn-65	9.74E-06	8.15E-04

Table 5-25. Humid site annual fractional advective release rates for concepts using vaults.

	Humid-high percolation rate		Humid-low percolation rate	
	(Covered vault only)			
	Low	High	Low	High
Am-241	5.64E-03	4.08E-02	2.82E-04	2.04E-03
C-14	4.08E-02	3.00E-01	2.04E-03	1.50E-02
Ce-141	4.71E-04	3.00E-01	2.35E-05	1.50E-02
Ce-144	4.71E-04	3.00E-01	2.35E-05	1.50E-02
Cm-241	5.64E-03	4.08E-02	2.82E-04	2.04E-03
Cm-244	5.64E-03	4.08E-02	2.82E-04	2.04E-03
Co-58	2.29E-02	7.18E-02	1.15E-03	3.59E-03
Co-60	2.29E-02	7.18E-02	1.15E-03	3.59E-03
Cs-134	9.21E-04	3.00E-01	4.61E-05	1.50E-02
Cs-137	9.21E-04	3.00E-01	4.61E-05	1.50E-02
Fe-55	2.85E-02	7.18E-02	1.42E-03	3.59E-03
H-3	3.00E-01	3.00E-01	1.50E-02	1.50E-02
I-129	2.96E-01	3.00E-01	1.48E-02	1.50E-02
Mn-54	2.92E-03	3.00E-01	1.46E-04	1.50E-02
Nb-94	9.14E-03	1.84E-01	4.57E-04	9.20E-03
Ni-59	3.48E-02	7.18E-02	1.74E-03	3.59E-03
Ni-63	3.48E-02	7.18E-02	1.74E-03	3.59E-03
Pu-238	4.64E-03	4.08E-02	2.32E-04	2.04E-03
Pu-239	4.64E-03	4.08E-02	2.32E-04	2.04E-03
Pu-240	4.64E-03	4.08E-02	2.32E-04	2.04E-03
Pu-241	4.64E-03	4.08E-02	2.32E-04	2.04E-03
Sr-90	1.95E-03	3.00E-01	9.76E-05	1.50E-02
Tc-99	1.49E-02	3.00E-01	7.47E-04	1.50E-02
Zn-65	3.58E-03	3.00E-01	1.79E-04	1.50E-02

Table 5-26. Humid site annual fractional advective release rates for concepts using concrete canisters.

	Humid-high percolation rate		Humid-low percolation rate	
	(Covered vault only)			
	Low	High	Low	High
Am-241	1.23E-02	8.87E-02	6.13E-04	4.43E-03
C-14	8.87E-02	6.52E-01	4.43E-03	3.26E-02
Ce-141	1.02E-03	6.52E-01	5.12E-05	3.26E-02
Ce-144	1.02E-03	6.52E-01	5.12E-05	3.26E-02
Cm-241	1.23E-02	8.87E-02	6.13E-04	4.43E-03
Cm-244	1.23E-02	8.87E-02	6.13E-04	4.43E-03
Co-58	4.99E-02	1.56E-01	2.49E-03	7.81E-03
Co-60	4.99E-02	1.56E-01	2.49E-03	7.81E-03
Cs-134	2.00E-03	6.52E-01	1.00E-04	3.26E-02
Cs-137	2.00E-03	6.52E-01	1.00E-04	3.26E-02
Fe-55	6.19E-02	1.56E-01	3.10E-03	7.81E-03
H-3	6.52E-01	6.52E-01	3.26E-02	3.26E-02
I-129	6.44E-01	6.52E-01	3.22E-02	3.26E-02
Mn-54	6.35E-03	6.52E-01	3.17E-04	3.26E-02
Nb-94	1.99E-02	4.00E-01	9.94E-04	2.00E-02
Ni-59	7.56E-02	1.56E-01	3.78E-03	7.81E-03
Ni-63	7.56E-02	1.56E-01	3.78E-03	7.81E-03
Pu-238	1.01E-02	8.87E-02	5.05E-04	4.43E-03
Pu-239	1.01E-02	8.87E-02	5.05E-04	4.43E-03
Pu-240	1.01E-02	8.87E-02	5.05E-04	4.43E-03
Pu-241	1.01E-02	8.87E-02	5.05E-04	4.43E-03
Sr-90	4.24E-03	6.52E-01	2.12E-04	3.26E-02
Tc-99	3.25E-02	6.52E-01	1.62E-03	3.26E-02
Zn-65	7.79E-03	6.52E-01	3.90E-04	3.26E-02

- Advective release rate

- Diffusive release rate

- High-integrity container/high-level-waste type container lifetime

- Period of time sealed source jacket prevents release

- Concrete canister/concrete vault lifetime.

The results calculated for each of the four waste category specific simulations for each disposal concept were combined to provide the total amount of radioactivity released should all GTCC LLW be disposed of using that concept.

Examining the results from the 40 probabilistic simulations (shown in Figure 5-6) identified the set of additional simulations necessary to evaluate performance in terms of groundwater concentration and radiation doses. Concepts showing zero concentration in the groundwater and therefore a zero dose at the end of the 100,000-year simulation period did not require a second set of performance simulations. For those concepts producing a groundwater concentration, a second set of probabilistic simulations was developed. For this second set of simulations, the 100,000-year simulation period was divided into 2,500-year increments. The groundwater concentration and radiation dose for each of these 40 increments was examined. For each of the 40 increments, results for 250 iterations, each using a different set of variable parameter values, were calculated.

Total Releases from the Near-Surface Disposal Concepts. The mean value for the total release for each of the 40 near surface disposal concept performance simulations is shown in Tables 5-27 through 5-31. Table 5-27 lists the mean value for the total amount of radioactivity released from each near-surface disposal concept if only activated metals were disposed of. The amount of activity released is shown along with the percent of the initial inventory this value represents. A "yes" in the left hand column means radioactivity reaches the groundwater by the end of the 100,000-year simulation period. Similar information is provided for the near-surface disposal concepts containing process waste, contaminated equipment and material, or sealed sources in Tables 5-28, 5-29, and 5-30, respectively. Table 5-31 reports the total activity release when all GTCC LLW is disposed of in each near-surface disposal concept.

Table 5-27. Total releases from near-surface disposal concepts - activated metals.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Shallow-land disposal/arid	6.0E+04	0.16	Yes
Shallow-land disposal/humid	6.0E+04	0.16	Yes
Modular concrete canister/arid	6.0E+04	0.16	Yes
Modular concrete canister/humid	5.8E+04	0.16	Yes
Aboveground vault/arid	5.5E+04	0.15	Yes
Aboveground vault/humid	5.5E+04	0.15	Yes
Earth-mounded vault/arid	5.7E+04	0.15	Yes
Earth-mounded vault/humid	5.4E+04	0.15	Yes
Belowground vault/arid	5.7E+04	0.15	Yes
Belowground vault/humid	5.4E+04	0.15	Yes

sources) a total of 104 individual probabilistic or deterministic simulations were made. The calculated performance for any one concept for each of the four waste categories is combined to produce the performance for that concept were it to dispose of all four categories of the GTCC LLW.

Intrusion is evaluated by grouping similar facilities and then evaluating the intrusion potential and consequences for each grouping. The four near surface disposal concept using an earthen cover (shallow-land disposal, belowground vault, modular concrete canister, and earth-mounded vault) is one group. The near-surface abovegrade vault is evaluated in its own group. The intermediate-depth and deep geologic drilled holes is the third group while the mined cavity, both intermediate-depth and deep geologic, is the final group.

5.3.1 Containment

The ability of 13 disposal concepts to contain the radioactivity associated with the GTCC LLW is judged by examining three measures of containment performance. As discussed in Section 3 these three measures are as follows:

- Total amount of radioactivity released from the disposal concept over the 100,000 year analysis period

- Concentration of radioactivity is the ground water in the near vicinity of the disposal concept

- Radiation dose to an individual consuming two liters per day of contaminated ground water.

Near Surface Disposal Concepts. Figure 5-6 depicts the 40 disposal concept probabilistic performance simulations made to determine the total amount of radioactivity released from the five near-surface disposal concepts. Each probabilistic simulation is made up of 1,000 iterations. For each iteration, a value from within the range for each variable parameter described in Section 4 is randomly selected and performance is calculated. The variable parameters for which random values were selected are as follows:

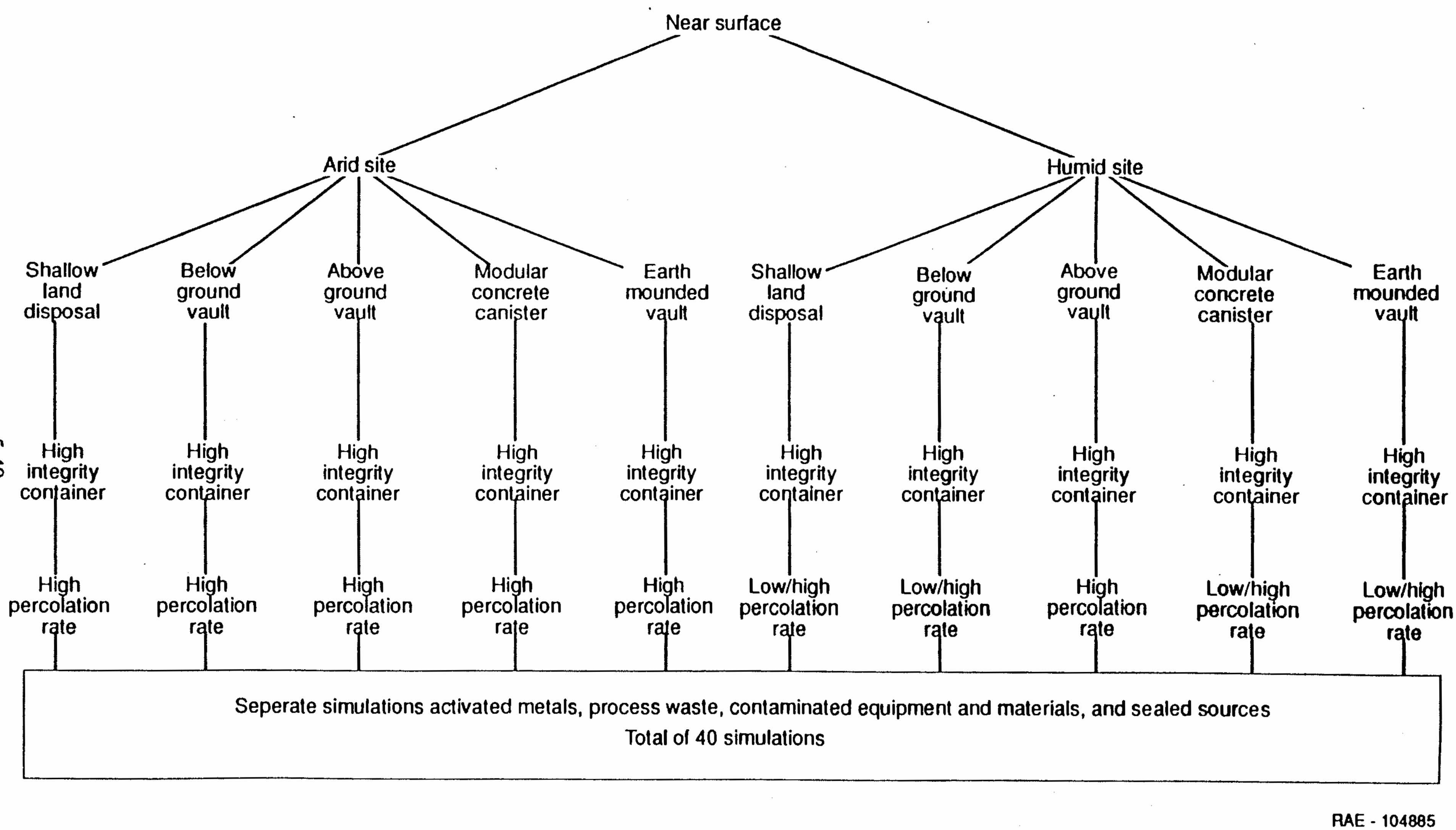


Figure 5-6. Performances simulations for near surface disposal concepts.

Table 5-28. Total releases from near-surface disposal concepts - process waste.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Shallow-land disposal/arid	6.2E+02	0.12	Yes
Shallow-land disposal/humid	1.7E+03	0.34	Yes
Modular concrete canister/arid	3.5E+02	0.07	Yes
Modular concrete canister/humid	6.2E+02	0.12	Yes
Aboveground vault/arid	2.3E+02	0.05	Yes
Aboveground vault/humid	3.8E+02	0.08	Yes
Earth-mounded vault/arid	2.4E+02	0.05	Yes
Earth-mounded vault/humid	3.7E+02	0.07	Yes
Belowground vault/arid	2.4E+02	0.05	Yes
Belowground vault/humid	3.7E+02	0.07	Yes

Table 5-29. Total releases from near-surface disposal concepts - contaminated equipment and material.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Shallow-land disposal/arid	6.6E+02	23.00	No
Shallow-land disposal/humid	1.4E+03	48.78	Yes
Modular concrete canister/arid	3.1E+02	10.80	No
Modular concrete canister/humid	9.0E+02	31.36	Yes
Aboveground vault/arid	2.0E+02	6.97	No
Aboveground vault/humid	4.9E+02	17.07	Yes
Earth-mounded vault/arid	1.9E+02	6.62	No
Earth-mounded vault/humid	4.7E+02	16.38	Yes
Belowground vault/arid	1.9E+02	6.62	No
Belowground vault/humid	4.7E+02	16.38	Yes

Table 5-30. Total releases from near-surface disposal concepts - sealed sources.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Shallow-land disposal/arid	1.1E+07	67.07	No
Shallow-land disposal/humid	1.2E+07	73.17	Yes
Modular concrete canister/arid	6.4E+06	39.02	No
Modular concrete canister/humid	1.2E+07	73.17	Yes
Aboveground vault/arid	4.4E+06	26.83	No
Aboveground vault/humid	1.2E+07	73.17	Yes
Earth-mounded vault/arid	4.4E+06	26.83	No
Earth-mounded vault/humid	1.2E+07	73.17	Yes
Belowground vault/arid	4.4E+06	26.83	No
Belowground vault/humid	1.2E+07	73.17	Yes

Table 5-31. Total releases from near-surface disposal concepts - all GTCC LLW.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Shallow-land disposal/arid	1.1E+07	20.41	Yes
Shallow-land disposal/humid	1.2E+07	22.26	Yes
Modular concrete canister/arid	6.5E+06	11.92	Yes
Modular concrete canister/humid	1.2E+07	22.25	Yes
Aboveground vault/arid	4.5E+06	8.22	Yes
Aboveground vault/humid	1.2E+07	22.24	Yes
Earth-mounded vault/arid	4.5E+06	8.22	Yes
Earth-mounded vault/humid	1.2E+07	22.24	Yes
Belowground vault/arid	4.5E+06	8.22	Yes
Belowground vault/humid	1.2E+07	22.24	Yes

The performance of the five near-surface disposal concepts are equal with regard to radionuclides having half lives of about 20 years or less. The high-integrity container used in all the near-surface, and half the intermediate-depth and deep geologic disposal concepts provides complete containment of the inventory for a minimum of 200 years. Thus, the activity assigned to H-3, Mn-54, Fe-55, Co-58, Co-60, Zn-65, Cs-134, Ce-141, Ce-144, Pu-241, Cm-242, and Cm-144 will have, at a minimum, been reduced by a factor of 9.8E-04. Decay alone reduces the inventory available for release for each of ten of these 12 radionuclides to the values less than 10 curies. Activities on the order of 1,000 Ci will still be present after 200 years for Fe-55 and Co-60.

The benefit of the 200-year decay period is not equal for all four waste categories. The activated metals and process waste categories have a larger percentage of their total activity made up of radionuclides with half lives of 20 years or less. A larger fraction of their initial inventory is therefore not available once releases could occur. This reduction in the inventory available for release is reflected in the percent columns of Tables 5-27 and 5-28. Therefore, all the activity available for release at year 200 or 300 could in fact occur and the percent released column in Tables 5-27 or 5-25 would still be less than 100 percent.

The results given in Table 5-27 indicate that there is only a small difference among the near-surface disposal concepts in their ability to contain the radionuclides in the activated metal waste category. Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 are released in similar amounts for all of the near-surface disposal concepts. The extremely low rate of radionuclide mobilization from the metal components due to corrosion results in a total release that is less than 1% of the total initial inventory. A portion of the radionuclides released from the disposal concepts at both the arid and humid sites are projected to reach the groundwater during the 100,000-year simulation period. Six radionuclides, C-14, Nb-94, Ni-59, I-129, Pu-239 and Tc-99 reach the groundwater at the humid site while only C-14, I-129, and Tc-99 will reach the groundwater at the arid site.

Process waste is confined by the GTCC LLW disposal concepts to different degrees at the two disposal sites. The results of the probabilistic calculations, Table 5-28, show that shallow-land disposal at either the arid or humid site has the highest total release. Shallow-land disposal at the humid site has a total release almost three times greater than the release at the arid site.

For the other four near-surface disposal concepts, the releases at the humid site exceed those at the arid site by a factor of 1.4 to 1.7. The belowground, aboveground, and earth-mounded vaults exhibit identical performance at the arid site and essentially equal performance at the humid site. Modular concrete canisters produce releases that are 56% and 36%, respectively, of the releases from arid and humid shallow-land disposal. These releases are 50 to 63% greater than the arid and humid releases for the vault concepts.

The radionuclides comprising the total release of process waste radioactivity are the same, regardless of disposal concept and site. They include Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 are all released. Of these radionuclides, C-14, Ni-59, Nb-94, I-129, Pu-239, and Tc-99 reach the groundwater during the 100,000 year simulation period at the humid site while only C-14, I-129, and Tc-99 reach the groundwater at the arid site.

Releases of radioactivity associated with contaminated equipment and material from near-surface disposal concepts at the arid site are smaller than releases for the same concept at the humid site. Total releases at the arid site are 34 to 49% of those at the humid site, for the same concept. The radionuclides released from the disposal concepts are the same for both sites, and include Am-241, Cs-137, Pu-238, Pu-239, Pu-241, and Sr-90. The three concepts employing concrete vaults are the most effective at the two sites, while shallow-land disposal produces the greatest total releases. None of the radionuclides released from the disposal concepts reach the groundwater at the arid site during the 100,000 year evaluation period, while they do reach the groundwater at the humid site.

Radionuclides released from the sealed source waste include Am-241, Cs-137, Cm-244, Pu-238, Pu-239, Pu-240, and Pu-241. The activity released from the disposal concepts reaches the groundwater at the humid site during the 100,000 year simulation period. None of the activity released reaches the groundwater at the arid site. As shown in Table 5-30, the total release at the humid site is the same for all five near-surface concepts. The releases at the arid site varies by concept, with shallow-land disposal producing the largest release and the three concepts using vaults producing the smallest. Whereas the majority of the concepts are more effective at the arid site, the shallow-land disposal concept is most effective at the humid site.

Table 5-31 reports the composite performance of each near-surface disposal concept when all GTCC LLW id disposed of in each concept. The values of total activity released are the sum of the values presented in Tables 5-27 through 5-30. The percent of initial inventory is based on the 5.41E+07 curies assigned in Section 4. Comparison of the results in Table 5-31 to those for the individual waste categories, identifies sealed sources as the dominant waste category. Comparison of the total releases reported in Tables 5-30 and 5-31 shows that the composite total release is either equal to or only slightly greater than the releases resulting from sealed sources.

Based on the percent of initial inventory released, all five concepts result in essentially equal release at the humid site. Shallow-land disposal at the arid site results in a total release that is 92% of the release at the humid site. The three concepts using vaults at the arid site have total releases that are 37% of the total release for the same concept at the humid site and are 40% of the total release for arid site shallow-land disposal. Arid site modular concrete canisters produce releases that are 45% greater than the total releases associated with the concepts using vaults.

Groundwater Concentrations. The 40 probabilistic simulations used to determine the total release from the near-surface disposal concepts were used to identify the concepts for which a second set of probabilistic simulations would be performed. For each disposal concept and site concept where radionuclides reached the groundwater during the 100,000-year simulation period, a second simulation was performed. This second set of simulations was performed to determine the variability of radionuclide groundwater concentration and radiation dose over time. The 100,000-year simulation period was divided into 40, 2,500-year intervals. For each interval, results for 250 randomly selected combinations of variable parameters were calculated. The results are used to assess the impact of each disposal concept on the environment, and is the basis for determining relative health impacts to persons drinking contaminated groundwater. Generally, a subset of the radionuclides released from a given disposal concept reach the groundwater during the 100,000 year simulation period. Retardation of the remaining radionuclides delays their arrival until some point after this time.

Table 5-32 reports the peak groundwater concentration resulting from release from the near-surface disposal concepts at both the arid and humid sites. Also reported are the times when radionuclides first reach the groundwater and when the peak groundwater concentration occurs. Radioactivity typically reaches the groundwater at the humid site with 5,000 years. The travel time at the arid site is a factor of 10 to 20 times greater. For activated metals and process wastes, radioactivity reaches the groundwater at both sites. The concentration at the humid site is three to four orders-of-magnitude greater than at the arid site.

Table 5-32. Near-surface groundwater concentrations.

	Shallow-land disposal			Modular concrete canister			Aboveground vault			Earth-mounded vault			Belowground vault		
	Time of 1st arrival (yr)	Time of peak conc. (yr)	Peak conc. (Ci/ft³)	Time of 1st arrival (yr)	Time of peak conc. (yr)	Peak conc. (Ci/ft³)	Time of 1st arrival (yr)	Time of peak conc. (yr)	Peak conc. (Ci/ft³)	Time of 1st arrival (yr)	Time of peak conc. (yr)	Peak conc. (Ci/ft³)	Time of 1st arrival (yr)	Time of peak conc. (yr)	Peak conc. (Ci/ft³)
Activated metals															
Arid	57,500	100,000	1.4E-6	57,500	87,500	8.3E-7	62,500	75,000	4.6E-8	60,000	92,500	8.0E-7	57,500	90,000	8.1E-7
Humid	<5,000	15,000	5.3E-2	<5,000	15,000	5.3E-2	<5,000	42,500	2.5E-2	<5,000	47,500	2.4E-2	<5,000	20,000	4.9E-2
Process waste															
Arid	57,500	92,500	5.7E-7	57,500	72,500	9.5E-7	60,000	82,500	2.8E-7	60,000	87,500	3.0E-7	57,500	77,500	2.8E-7
Humid	<5,000	5,000	7.6E-4	<5,000	5,000	9.7E-4	<5,000	5,000	1.6E-3	<5,000	5,000	4.9E-3	<5,000	5,000	5.2E-3
Contaminated solids															
Arid	>100,000	---	---	>100,000	---	---	>100,000	---	---	>100,000	---	---	>100,000	---	---
Humid	<5,000	5,000	2.3E-3	<5,000	5,000	2.8E-3	<5,000	12,500	4.2E-4	<5,000	12,500	3.0E-3	<5,000	5,000	6.7E-3
Sealed sources															
Arid	>100,000	---	---	>100,000	---	---	>100,000	---	---	>100,000	---	---	>100,000	---	---
Humid	<5,000	15,000	4.0E+2	<5,000	5,000	1.5E+2	<5,000	15,000	2.5E+1	<5,000	27,500	2.6E+0	<5,000	12,500	5.1E+1

Radiation Doses. Radiation doses to an individual consuming contaminated groundwater are calculated for the near-surface disposal concepts where contaminated groundwater occurs. The annual doses resulting from consumption of groundwater are reported in Table 5-33. As with groundwater concentration, peak doses at the arid site occur much later than at the humid site. Similarly, the peak doses at the arid sites are three to five orders-of-magnitude less than at the humid site.

Intermediate-Depth Disposal Concepts. Figure 5-7 depicts the 32 disposal concept probabilistic performance simulations made to determine the total amount of radioactivity released from the four intermediate-depth disposal concepts. Each probabilistic simulation is made up of 1,000 iterations. For each iteration, a value from within the range for each variable parameter described in Section 4.0 is randomly selected and performance is calculated. The results for the four waste category specific simulations for each disposal concept were combined to provide the total amount of radioactivity released should all GTCC LLW be disposed of using that concept.

Examining of the results from the 32 probabilistic simulations (shown in Figure 5-7) identified the set of additional simulations necessary to evaluate performance in terms of groundwater concentration and radiation doses. Concepts showing zero concentration in the groundwater and therefore a zero dose at the end of the 100,000 year simulation period did not require analysis against the second and third confinement performance measure. The groundwater analysis divided the 100,000-year simulation period into 40, 2,500-year intervals. For each interval, the results for 250 randomly selected parameter values were calculated. These results were used to estimate the variability of groundwater concentrations and radiation doses over time.

Total Releases from Intermediate-Depth Disposal Concepts. The mean value for the total release for each of the 32 intermediate-depth disposal concept performance simulations is shown in Tables 5-34 through 5-38. Table 5-34 lists the mean value for the total amount of radioactivity released from each intermediate-depth disposal concept if it were only used for activated metals. Also listed is the percentage this value represents of the initial inventory. It is also indicated if any radionuclides reached the ground water during the 100,000-year simulation period. Tables 5-35, 5-36, and 5-37 list the same information for the concepts if each were to contain only process waste, contaminated equipment and material, and sealed sources, respectively. Table 5-38 displays the mean value and percentages of the initial inventory for the total expected release should any one concept be used to dispose of all the GTCC LLW.

Table 5-33. Near-surface radiation doses.

	Shallow-land disposal		Modular concrete canister		Aboveground vault		Earth-mounded vault		Belowground vault	
	Time of peak dose (yr)	Peak dose (mrem/yr)	Time of peak dose (yr)	Peak dose (mrem/yr)	Time of peak dose (yr)	Peak dose (mrem/yr)	Time of peak dose (yr)	Peak dose (mrem/yr)	Time of peak dose (yr)	Peak dose (mrem/yr)
Activated metals										
Arid	100,000	2.4E+2	100,000	2.2E+2	100,000	1.7E+2	100,000	2.0E+2	100,000	2.1E+2
Humid	5,000	8.8E+5	5,000	8.8E+5	7,500	5.6E+5	7,500	5.6E+5	7,500	6.4E+5
Process waste										
Arid	92,500	4.1E+3	72,500	6.7E+3	82,500	2.0E+3	87,500	2.2E+3	77,500	2.0E+3
Humid	5,000	8.4E+7	5,000	1.0E+8	15,000	1.8E+8	15,000	1.6E+7	5,000	2.5E+8
Contaminated solids										
Arid	---	---	---	---	---	---	---	---	---	---
Humid	5,000	2.5E+8	5,000	3.1E+8	12,500	4.6E+7	12,500	3.3E+8	5,000	7.4E+8
Sealed sources										
Arid	---	---	---	---	---	---	---	---	---	---
Humid	15,000	4.4E+13	5,000	1.6E+13	15,000	2.7E+12	27,500	2.8E+11	12,500	5.6E+12

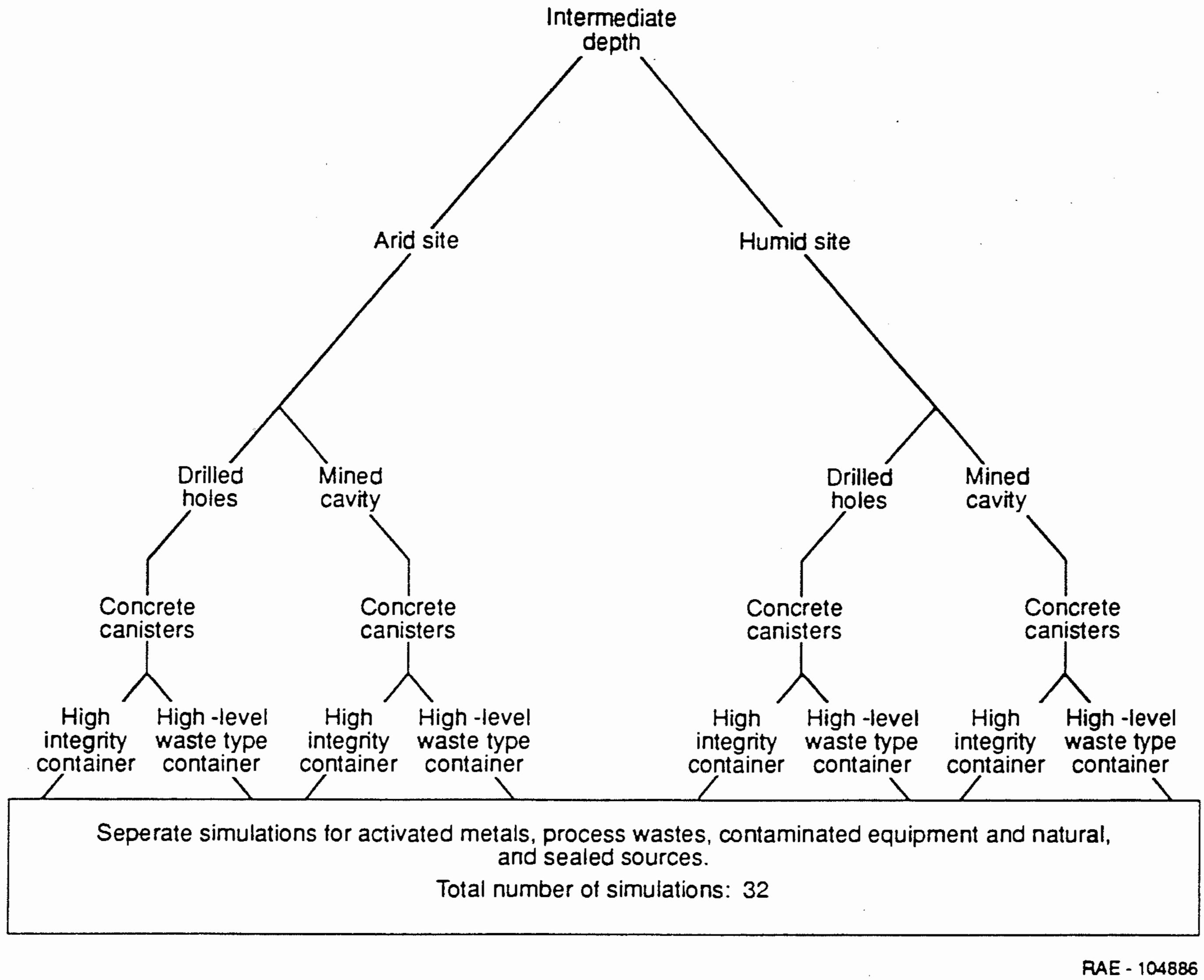


Figure 5-7. Performance simulations for intermediate depth disposal concepts.

Table 5-34. Total releases from intermediate-depth disposal concepts - activated metals.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	5.8E+04	0.16	Yes
Drilled hole/humid/high-integrity container	5.7E+04	0.15	Yes
Mined cavity/arid/high-integrity container	5.8E+04	0.16	Yes
Mined cavity/humid/high-integrity container	5.7E+04	0.15	Yes
Drilled hole/arid/high-level-waste type container	5.7E+04	0.15	Yes
Drilled hole/humid/high-level-waste type container	5.7E+04	0.15	Yes
Mined cavity/arid/high-level-waste type container	5.7E+04	0.15	Yes
Mined cavity/humid/high-level-waste type container	5.7E+04	0.15	Yes

Table 5-35. Total releases from intermediate-depth disposal concepts - process waste.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	4.3E+02	0.09	Yes
Drilled hole/humid/high-integrity container	5.7E+02	0.11	Yes
Mined cavity/arid/high-integrity container	4.2E+02	0.08	Yes
Mined cavity/humid/high-integrity container	5.7E+02	0.11	Yes
Drilled hole/arid/high-level-waste type container	3.1E+02	0.06	Yes
Drilled hole/humid/high-level-waste type container	4.6E+02	0.09	Yes
Mined cavity/arid/high-level-waste type container	3.0E+02	0.06	Yes
Mined cavity/humid/high-level-waste type container	4.6E+02	0.09	Yes

Table 5-36. Total releases from intermediate-depth disposal concepts - contaminated equipment and material.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	3.9E+02	13.45	No
Drilled hole/humid/high-integrity container	7.7E+02	26.55	No
Mined cavity/arid/high-integrity container	3.6E+02	12.41	No
Mined cavity/humid/high-integrity container	7.8E+02	26.90	No
Drilled hole/arid/high-level-waste type container	3.0E+02	10.34	No
Drilled hole/humid/high-level-waste type container	6.4E+02	22.07	No
Mined cavity/arid/high-level-waste type container	2.9E+02	10.00	No
Mined cavity/humid/high-level-waste type container	6.4E+02	22.07	No

Table 5-37. Total releases from intermediate-depth disposal concepts - sealed sources.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	6.4E+06	40.00	No
Drilled hole/humid/high-integrity container	1.2E+07	75.00	No
Mined cavity/arid/high-integrity container	6.5E+06	40.63	No
Mined cavity/humid/high-integrity container	1.2E+07	75.00	No
Drilled hole/arid/high-level-waste type container	6.4E+06	40.00	No
Drilled hole/humid/high-level-waste type container	1.2E+07	75.00	No
Mined cavity/arid/high-level-waste type container	6.4E+06	40.00	No
Mined cavity/humid/high-level-waste type container	1.2E+07	75.00	No

Table 5-38. Total releases from intermediate-depth disposal concepts - all GTCC LLW.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	6.5E+06	12.07	Yes
Drilled hole/humid/high-integrity container	1.2E+07	22.43	Yes
Mined cavity/arid/high-integrity container	6.6E+06	12.26	Yes
Mined cavity/humid/high-integrity container	1.2E+07	22.54	Yes
Drilled hole/arid/high-level-waste type container	6.5E+06	12.07	Yes
Drilled hole/humid/high-level-waste type container	1.2E+07	22.43	Yes
Mined cavity/arid/high-level-waste type container	6.4E+06	11.97	Yes
Mined cavity/humid/high-level-waste type container	1.2E+07	22.54	Yes

As explained previously for the near-surface disposal concepts, the minimum life of the waste package is reflected in the percent of initial inventory column in Tables 5-34 through 5-38. The use of a high-integrity container with a minimum lifetime of 200 years reduces by a factor of 9.8E-04, the amount of the initial inventory available for release. The use of a high-level-waste type container with a minimum lifetime of 300 years will produce an even greater benefit.

The benefit of the 200 or 300 year decay period is not equal for all four waste categories. The activated metals and process waste categories have a larger percentage of their total activity made up of radionuclides with half lives of 20 years or less. A larger fraction of their initial inventory is therefore not available once releases could occur. This reduction in the inventory available for release will be reflected in the percent columns of Tables 5-34 through 5-38. Therefore, all the activity available for release at year 200 or 300 could in fact occur and the percent released column in Tables 5-34 through 5-38 would still be less than 100 percent.

Table 5-34 shows there is no difference in the ability of the intermediate-depth disposal concepts to contain the radioactivity associated with activated metals. Regardless of disposal concept, Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 will be released. The total release is less than 1% of the initial inventory due to the very low rate at which the metal components corrode and thereby free the radionuclides for transport out of the disposal unit. The only radionuclides reaching the ground water even under the most favorable transport conditions (low retardation and high conductivity) are C-14, I-129, and Tc-99.

The ability of the intermediate-depth disposal concepts to contain process wastes varies based on site characteristics. Based on the probabilistic calculations summarized in Table 5-35, the arid site concepts perform 25 to 35% better than the same concepts at the humid site. The arid site drilled hole concept, has total releases that are 25 to 33% less than those for the drilled hole concept at the humid site. Similarly the arid mined cavity has a total release 26 to 35% of that seen for the humid site. The difference in performance between the drilled hole concept and the mined cavity concept at the same site is less than 1% based on the mean value for total curies released.

The radionuclides making up the total release are the same, regardless of disposal concept and site. Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 are all released. (A few of the calculations indicate that some Cs-134 may be released. The amount is calculated to be on the order of 1E-30 or less and to occur in less than 50 of the 1,000 iterations performed. Based on the extremely low value and the low potential for its occurrence, a value of zero was assigned for the amount of Cs-134 released.) Of the radionuclides released only C-14, I-129, and Tc-99 reach the ground water.

For containment of the radioactivity associated with the contaminated equipment and material (Am-241, Sr-90, Cs-137, Pu-238, Pu-239, and Pu-241) the mined cavity or the drilled hole concepts using a high-level-waste type container at the arid site have the lowest total release. The release for these concepts are 55% less than the release for the same concept at the humid site and is 18% lower than the release for the use of a high-integrity container at the arid site as shown in Table 5-36. The total release is made up of some activity for each radionuclide assigned to the contaminated equipment and material category. None of the activity released reaches the ground water at either the arid or humid sites, even under the most favorable transport conditions analyzed.

For the sealed source waste category, Am-241, Cs-137, Cm-244, Pu-238, Pu-239, Pu-240, and Pu-241 make up the release. None of the activity released reaches the ground water at either site. There is no difference in performance between the drilled hole and the mined cavity and none between high-integrity containers and high-level-waste type containers. As shown in Table 5-37 either of the disposal concepts located at the arid site will result in releases that are 47% lower than the same concept at the humid site.

Table 5-38 presents the composite performance of each intermediate-depth disposal concept should all GTCC LLW be disposed of together. The values for total activity released are the sum of the values listed in Tables 5-34 through 5-37. The percent of initial inventory is based on the 5.41E+07 curies assigned in Section 4. Comparison of these results to those for the individual waste categories shows sealed sources as the dominant waste category; to the point that the values for total release are identical. Based on the percent of initial inventory released data, the releases from any of the intermediate-depth disposal concepts at an arid site are 47% less than the release for the same technology at the humid site. There is no discernable difference in performance of the intermediate-depth drilled hole and mined cavity concepts at the arid site.

Groundwater Concentration. Based on the 32 probabilistic simulations performed to determine the total release from the intermediate depth concepts, 16 of the concepts released radioactivity that reached the ground water within the 100,000-year analysis period. Probabilistic computer calculations were performed to determine the change in groundwater concentration over time. The same calculations, using DOE internal dose conversion factors (DOE 1988), provided the change in potential radiation dose over time.

The concentration of GTCC LLW radionuclides in the ground water over time is examined to judge the impact of the disposal concepts on the environment and as a precursor to determining the potential impact on individuals. The data in Tables 5-34 through 5-38 shows releases reaching the ground water for all the intermediate-disposal concepts used to dispose of the activated metal and process waste categories. While significant quantities of radioactivity are released from intermediate-depth concepts containing contaminated equipment and material and sealed sources, this radioactivity does not reach the ground water before the end of the 100,000-year simulation period. Retardation of the radionuclides released from these two waste categories delay their arrival in the aquifer to after the end of the simulation period.

C-14, I-129, and Tc-99 are the only three radionuclides reaching the ground water within 100,000 years. Only the activated metal and process waste categories contain these radionuclides. Impact on the environment is therefore judged by examining the variation over time in ground water concentration for these three radionuclides.

Table 5-39 lists the total concentration of radioactivity in the groundwater. All is contributed by C-14, I-129, and Tc-99 for each of the eight intermediate-depth disposal concepts. The concentrations listed are the mean value based on 250 iterations for each of 40, 2,500-year time intervals. Also listed are the times when the radioactivity first reaches the groundwater and the time when the peak concentration occurs.

The groundwater concentration at the arid site is three to four orders of magnitude lower than the concentrations resulting from the same disposal concept at the humid site. Based on the concentration in the groundwater the mined cavity and the drilled hole offer essentially equivalent performance.

The radionuclide concentration in the groundwater from the process waste category is listed in Table 5-40. The relative performance of the intermediate-depth disposal concepts when used for process waste is the same as for activated metals. Concepts used at the arid site result in concentrations of radioactivity in the ground water about an order of magnitude lower than those for the humid site.

Table 5-39. Intermediate-depth groundwater concentration - activated metals.

	Year radioactivity initially reaches groundwater	Year of peak concentration	Total
Drilled hole/arid/high-integrity container	40,000	100,000	3.0E-07
Drilled hole/humid/high-integrity container	7,500	12,500	1.2E-04
Mined cavity/arid/high-integrity container	47,500	80,000	5.7E-07
Mined cavity/humid/high-integrity container	7,500	10,000	3.1E-04
Drilled hole/arid/high-level-waste type container	42,500	97,500	3.8E-07
Drilled hole/humid/high-level-waste type container	7,500	12,500	1.2E-04
Mined cavity/arid/high-level-waste type container	47,500	82,500	5.5E-07
Mined cavity/humid/high-level-waste type container	7,500	12,500	2.8E-04

Table 5-40. Intermediate-depth groundwater concentration - process waste.

	Year radioactivity initially reaches groundwater	Year of peak concentration	Total
Drilled hole/arid/high-integrity container	40,000	47,500	3.0E+02
Drilled hole/humid/high-integrity container	7,500	7,500	3.3E-05
Mined cavity/arid/high-integrity container	45,000	85,000	1.3E-07
Mined cavity/humid/high-integrity container	7,500	7,500	8.5E-05
Drilled hole/arid/high-level-waste type container	40,000	47,500	9.6E-08
Drilled hole/humid/high-level-waste type container	7,500	7,500	2.5E-05
Mined cavity/arid/high-level-waste type container	45,000	62,500	1.9E-07
Mined cavity/humid/high-level-waste type container	7,500	7,500	7.1E-05

Radiation Doses. When originally defined, the radiation dose performance measure was to account for the variation in the impact on human health produce by the various radionuclides contained in GTCC LLW. It is assumed an individual consumes two liters of groundwater per day. All groundwater brought to the surface and consumed contains radioactivity at the levels reported in the previous subsection. Application of internal dose conversion factor to the reported groundwater concentration produces the resulting radiation dose for each disposal concept. Table 5-41 reports the peak annual radiation dose for the intermediate-depth disposal concept and waste type combinations producing groundwater contamination. For the most part, peak doses coincide with peak groundwater concentrations. There are a few instances where the peak dose occurs at a different time. This is a result of the three contributing radionuclides having different internal dose conversion factors.

As shown in Table 5-41, doses resulting at the arid site are 1 to 2 orders-of-magnitude less than those for the same concept at the humid site. Additionally, peak doses at the arid site occur significantly later in time; at year 40,000 to 100,000 versus 7,500 to 12,500 for the humid concepts. For the arid site, drilled holes using high-integrity containers result in the lowest peak doses, with drilled holes using high-level-waste type containers resulting in doses that are only slightly higher.

Deep Geologic Disposal Concepts. Figure 5-8 depicts the 32 disposal concept probabilistic performance simulations made to determine the total amount of radioactivity released from the four deep geologic disposal concepts. Each probabilistic simulation is made up of 1,000 iterations. For each iteration, a value from within the range for each variable parameter described in Section 4 was randomly selected and performance was calculated. The results for the four waste category specific simulations for each disposal concept were combined to provide the total amount of radioactivity released should all GTCC LLW be disposed of using that concept.

Examining of the results from the 32 probabilistic simulations (shown in Figure 5-8) identified the set of additional simulations necessary to evaluate performance in terms of groundwater concentration and radiation doses. Concepts showing zero concentration in the ground water and therefore a zero dose at the end of the 100,000-year simulation period did not require a second performance simulation. For those concepts producing a groundwater concentration, a second probabilistic calculation was made. The 100,000-year simulation was divided into 40, 2,500-year intervals. For each interval, results were calculated for 250 combinations of randomly selected variable values.

Table 5-41. Intermediate-depth peak radiation dose.

	Activated metals		Process Waste	
	Year of occurrence	Dose (mrem/yr)	Year of occurrence	Dose (mrem/yr)
Drilled hole/arid/high-integrity container	100,000	5.1E+01	55,000	2.7E+02
Drilled hole/humid/high-integrity container	12,500	5.3E+03	7,500	5.7E+03
Mined cavity/arid/high-integrity container	100,000	1.0E+02	85,000	9.3E+02
Mined cavity/humid/high-integrity container	10,000	1.4E+07	7,500	1.4E+04
Drilled hole/arid/high-level-waste type container	97,500	5.3E+01	47,500	4.9E+02
Drilled hole/humid/high-level-waste type container	12,500	4.8E+03	7,500	3.5E+03
Mined cavity/arid/high-level-waste type container	95,000	1.0E+02	62,500	1.3E+03
Mined cavity/humid/high-level-waste type container	12,500	1.2E+04	9,500	1.2E+04

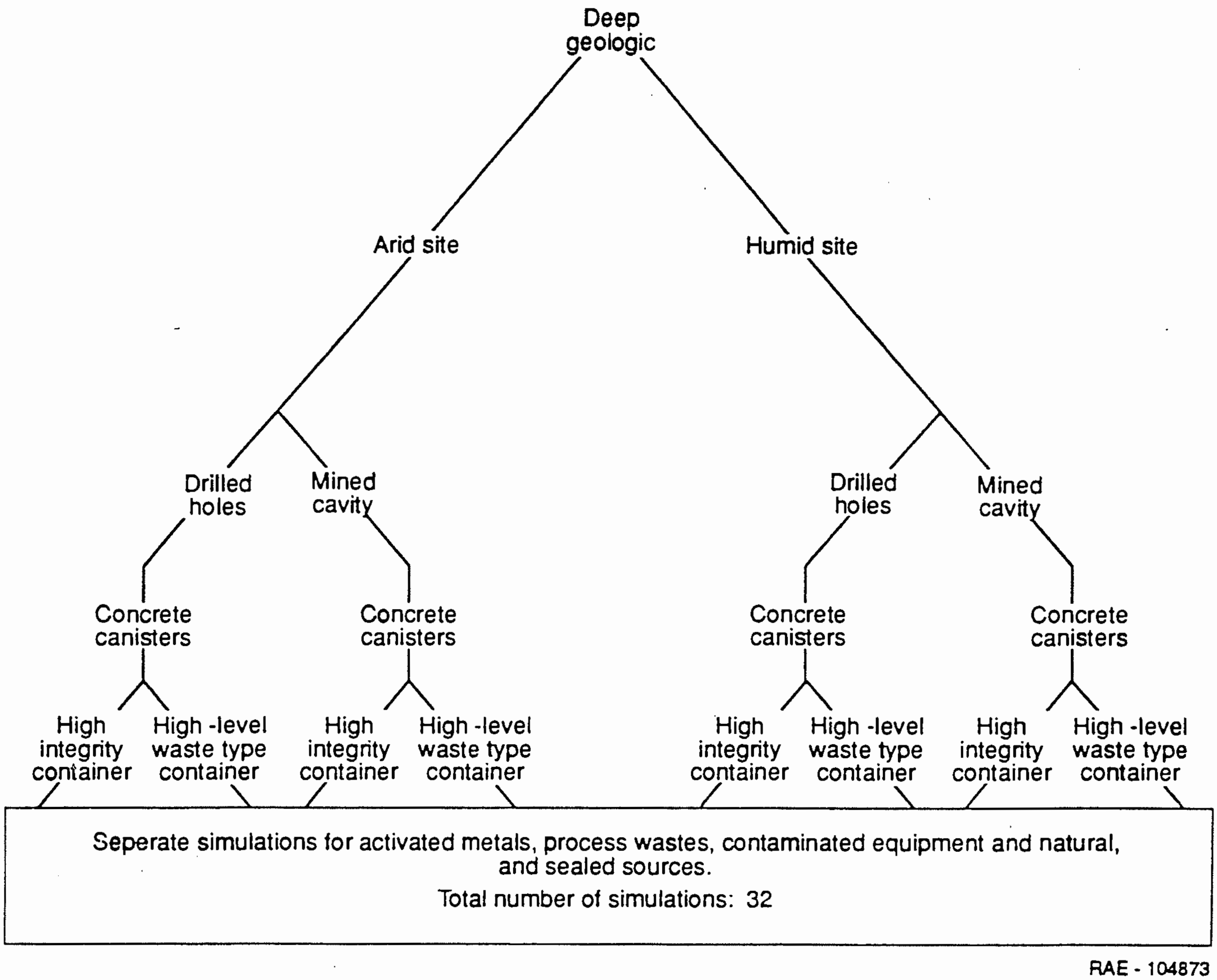


Figure 5-8. Performance simulations for deep geologic disposal concepts.

Total Releases from Deep Geologic Disposal Concepts. The mean value for the total release for each of the 32 deep geologic disposal concept performance simulations is shown in Tables 5-42 through 5-46. Table 5-42 lists the mean value for the total amount of radioactivity released from each deep geologic disposal concept if it were only used for activated metals. The percentage this value is of the initial inventory is also listed. It is indicated if radionuclides reach the ground water during the 100,000-year simulation period. Tables 5-43, 5-44, and 5-45 list the same information for the concepts if each were to contain only process waste, contaminated equipment and material, and sealed sources, respectively. Table 5-46 displays the minimum, mean, and maximum values for the total expected release should any one concept be used to dispose of all the GTCC LLW.

As explained previously for the near-surface disposal concepts, the minimum life of the waste package is reflected in the percent of initial inventory column in Tables 5-42 through 5-46. The use of a high-integrity container with a minimum lifetime of 200 years reduces by a factor of 9.8E-04, the amount of the initial inventory available for release. The use of a high-level-waste type package with a minimum lifetime of 300 years will produce a greater benefit.

The benefit of the 200 or 300 year decay period is not equal for all four waste categories. The activated metals and process waste categories have a larger percentage of their total activity made up of radionuclides with half lives of 20 years or less. A larger fraction of their initial inventory is therefore not available once releases could occur. This reduction in the inventory available for release will be reflected in the percent columns of Tables 5-42 through 5-46. Therefore, all the activity available for release at year 200 or 300 could in fact occur and the percent released column in Tables 5-42 through 5-46 would still be less than 100 percent.

Table 5-42 shows there is no difference in the ability of the deep geologic disposal concepts to contain the radioactivity associated with activated metals. Regardless of disposal concept, Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 will be released. The total release is less than one percent of the initial inventory due to the very low rate at which the metal components corrode and thereby free the radionuclides for transport out of the disposal unit. The only radionuclides reaching the ground water even under the most favorable transport conditions (low retardation and high conductivity) are C-14, I-129, and Tc-99.

The ability of the deep geologic concepts to contain process wastes varies based on site characteristics. Based on the probabilistic calculations summarized in Table 5-43, the arid site concepts

Table 5-42. Total releases from deep geologic disposal concepts - activated metals.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	5.8E+04	0.16	Yes
Drilled hole/humid/high-integrity container	5.7E+04	0.15	Yes
Mined cavity/arid/high-integrity container	5.8E+04	0.16	Yes
Mined cavity/humid/high-integrity container	5.7E+04	0.15	Yes
Drilled hole/arid/high-level-waste type container	5.7E+04	0.15	Yes
Drilled hole/humid/high-level-waste type container	5.7E+04	0.15	Yes
Mined cavity/arid/high-level-waste type container	5.7E+04	0.15	Yes
Mined cavity/humid/high-level-waste type container	5.7E+04	0.15	Yes

Table 5-43. Total releases from deep geologic disposal concepts - process waste.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	4.3E+02	0.09	Yes
Drilled hole/humid/high-integrity container	5.7E+02	0.11	Yes
Mined cavity/arid/high-integrity container	4.2E+02	0.08	Yes
Mined cavity/humid/high-integrity container	5.7E+02	0.11	Yes
Drilled hole/arid/high-level-waste type container	3.1E+02	0.06	Yes
Drilled hole/humid/high-level-waste type container	4.6E+02	0.09	Yes
Mined cavity/arid/high-level-waste type container	3.0E+02	0.06	Yes
Mined cavity/humid/high-level-waste type container	4.6E+02	0.09	Yes

Table 5-44. Total releases from deep geologic disposal concepts - contaminated equipment and material.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	3.9E+02	13.45	No
Drilled hole/humid/high-integrity container	7.7E+02	26.55	No
Mined cavity/arid/high-integrity container	3.6E+02	12.41	No
Mined cavity/humid/high-integrity container	7.8E+02	26.90	No
Drilled hole/arid/high-level-waste type container	3.0E+02	10.34	No
Drilled hole/humid/high-level-waste type container	6.5E+02	22.41	No
Mined cavity/arid/high-level-waste type container	2.9E+02	10.00	No
Mined cavity/humid/high-level-waste type container	6.4E+02	22.07	No

Table 5-45. Total releases from deep geologic disposal concepts - sealed sources.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	6.4E+06	40.00	No
Drilled hole/humid/high-integrity container	1.2E+07	75.00	No
Mined cavity/arid/high-integrity container	6.4E+06	40.00	No
Mined cavity/humid/high-integrity container	1.2E+07	75.00	No
Drilled hole/arid/high-level-waste type container	6.4E+06	40.00	No
Drilled hole/humid/high-level-waste type container	1.2E+07	75.00	No
Mined cavity/arid/high-level-waste type container	6.4E+06	40.00	No
Mined cavity/humid/high-level-waste type container	1.2E+07	75.00	No

Table 5-46. Total releases from deep geologic disposal concepts - all GTCC LLW.

	Total release (Ci)	% of initial inventory	Radionuclides reach the groundwater
Drilled hole/arid/high-integrity container	6.5E+06	12.07	Yes
Drilled hole/humid/high-integrity container	1.2E+07	22.43	Yes
Mined cavity/arid/high-integrity container	6.5E+06	12.07	Yes
Mined cavity/humid/high-integrity container	1.2E+07	22.54	Yes
Drilled hole/arid/high-level-waste type container	6.5E+06	12.07	Yes
Drilled hole/humid/high-level-waste type container	1.2E+07	22.43	Yes
Mined cavity/arid/high-level-waste type container	6.5E+06	12.07	Yes
Mined cavity/humid/high-level-waste type container	1.2E+07	22.54	Yes

perform 25 to 35 percent better than the same concepts at the humid site. The arid site drilled hole concept, has total releases that are 25 to 33% less than those for the drilled hole concept at the humid site. Similarly, the arid mined cavity has a total release 26 to 35% of that seen for the humid site. The difference in performance between the drilled hole concept and the mined cavity concept at the same site is less than one percent based on the mean value for total curies released.

The radionuclides making up the total release are the same, regardless of disposal concept and site. Am-241, C-14, Co-60, Cs-137, Fe-55, H-3, I-129, Nb-94, Ni-59, Ni-63, Pu-238, Pu-239, Pu-241, Sr-90, and Tc-99 are all released. (A few of the calculations indicate that some Cs-134 may be released. The amount is calculated to be on the order of 1E-30 or less and to occur in less than 50 of the 1,000 iterations performed. Based on the extremely low value and the low potential for its occurrence, a value of zero was assigned for the amount of Cs-134 released.) Of the radionuclides released only C-14, I-129, and Tc-99 reach the ground water.

For containment of the radioactivity associated with the contaminated equipment and material (Am-241, Sr-90, Cs-137, Pu-238, Pu-239, and Pu-241) the deep geologic mined cavity or drilled hole concepts using a high-integrity container at the humid site have the highest total release. As shown in Table 5-44, the release for these concepts are 55% more than the release for the same concept at the arid site and is 15 to 18% higher than the release for the use of a high-level-waste type container at the arid site. The total release is made up of some activity for each radionuclide assigned to the contaminated equipment and material category. None of the activity released reaches the ground water at either the arid or humid sites, even under the most favorable transport conditions analyzed.

For the sealed source waste category, Am-241, Cs-137, Cm-244, Pu-238, Pu-239, Pu-240, and Pu-241 make up the release. None of the activity released reaches the ground water at either site. There is no difference in performance between the drilled hole and the mined cavity and none between high-integrity containers and high-level-waste type containers. As shown in Table 5-45 any of the disposal concepts located at the arid site will result in releases that are 47% lower than the same concept at the humid site.

Table 5-46 presents the composite performance of each deep geologic disposal concept should all GTCC waste be disposed of together. The values for total activity released are the sum of the values listed in Tables 5-42 through 5-45. The percent of initial inventory is based on the 5.41E+07 curies assigned in Section 4. Comparison of these results to those for the individual waste categories shows sealed sources as the dominant waste category, to the point that the values for total release are identical. Based on the percent of initial inventory released data the releases from any of the deep geologic disposal concepts at an arid site are 47% less than the release for the same technology at the humid site. There is no discernable difference in performance of the deep geologic drilled hole and mined cavity concepts at the arid site.

Groundwater Concentration. Based on the 32 probabilistic simulations performed to determine the total release from the deep geologic concepts, 16 of the concepts released radioactivity that reached the groundwater within the 100,000-year analysis period. Probabilistic computer calculations were performed to determine the variability in groundwater concentration over time. The same calculations, using DOE internal dose conversion factors (DOE 1988), provided the variability in potential radiation dose over time.

Table 5-47 lists the total concentration of radioactivity in the groundwater. All is contributed by C-14, I-129, and Tc-99 for each of the eight deep geologic disposal concepts containing only activated metals. The concentrations listed are the mean value based on 250 interactions using randomly selected variable parameter values.

The groundwater concentration at the arid site is three to four orders of magnitude lower than the concentrations resulting from the same disposal concept at the humid site. Based on the concentration in the groundwater the mined cavity and the drilled hole offer essentially equivalent performance.

The concentration in the groundwater from the process waste category is listed in Table 5-48. The relative performance of the deep geologic disposal concepts when used for process waste is the same as for activated metals. Concepts used at the arid site result in concentrations of radioactivity in the groundwater about an order of magnitude lower than those for the humid site.

Radiation Doses. When originally defined, the radiation dose performance measure was to account for the variation in the impact on human health produced by the various radionuclides contained in GTCC LLW. It is assumed an individual consumes two liters of groundwater per day. All groundwater brought to the surface and consumed contains radioactivity at levels reported in the previous subsection. Application of internal dose conversion factors to the reported groundwater concentrations produces the resulting radiation dose for each disposal concept. Table 5-49 reports the peak annual radiation dose for the deep geologic concepts containing the categories of GTCC LLW that resulted in

Table 5-48. Deep geologic groundwater concentration - process waste.

	Year radioactivity initially reaches groundwater	Year of peak concentration	Total
Drilled hole/arid/high-integrity container	12,500	17,500	1.7E-06
Drilled hole/humid/high-integrity container	22,500	22,500	7.4E-07
Mined cavity/arid/high-integrity container	20,000	22,500	1.8E-06
Mined cavity/humid/high-integrity container	22,500	22,500	1.9E-06
Drilled hole/arid/high-level-waste type container	12,500	15,000	4.1E-06
Drilled hole/humid/high-level-waste type container	22,500	27,500	3.0E-06
Mined cavity/arid/high-level-waste type container	20,000	25,000	2.5E-06
Mined cavity/humid/high-level-waste type container	22,500	25,000	1.7E-06

Table 5-47. Deep geologic groundwater concentration - activated metals.

	Year radioactivity initially reaches groundwater	Year of peak concentration	Total
Drilled hole/arid/high-integrity container	12,500	20,000	1.3E-05
Drilled hole/humid/high-integrity container	22,500	27,500	7.4E-06
Mined cavity/arid/high-integrity container	20,000	27,500	9.9E-06
Mined cavity/humid/high-integrity container	22,500	100,000	1.9E-05
Drilled hole/arid/high-level-waste type container	12,500	20,000	1.2E-05
Drilled hole/humid/high-level-waste type container	22,500	100,000	7.4E-06
Mined cavity/arid/high-level-waste type container	20,000	27,500	8.8E-06
Mined cavity/humid/high-level-waste type container	22,500	100,000	1.9E-05

Table 5-49. Deep geologic peak radiation dose.

	Activated metals		Process Waste	
	Year of occurrence	Dose (mrem/yr)	Year of occurrence	Dose (mrem/yr)
Drilled hole/arid/high-integrity container	20,000	6.0E+02	25,000	8.7E+02
Drilled hole/humid/high-integrity container	27,500	3.6E+02	35,000	1.8E+03
Mined cavity/arid/high-integrity container	30,000	4.9E+02	25,000	2.4E+03
Mined cavity/humid/high-integrity container	100,000	9.4E+02	35,000	4.6E+03
Drilled hole/arid/high-level-waste type container	22,500	5.7E+02	15,000	1.6E+03
Drilled hole/humid/high-level-waste type container	100,000	3.7E+02	25,000	1.0E+03
Mined cavity/arid/high-level-waste type container	30,000	4.4E+02	27,500	2.7E+03
Mined cavity/humid/high-level-waste type container	100,000	9.5E+02	25,000	2.5E+03

Intruder Agricultural Scenario. The agricultural intruder inadvertently lives on and consumes food grown over the disposal facility and drills a water well for consumption and irrigation. The agriculture scenario is an applied extension of the intruder construction scenario, dirt from the excavated basement is spread around the home or farm. Since farming operations generally do not involve great depths, the waste will not be penetrated by plowing or other farming activities.

Intrusion Scenarios at Proposed GTCC Disposal Sites. The humid site in this report is considered to be a saturated environment. Near surface aquifers are present and higher precipitation occurs. The climate and the site characteristics define the site as a location where someone may want to live. There is a likelihood of future intrusion into the disposal site.

The arid site is considered to be an unsaturated disposal site. The general lithology for the hypothetical unsaturated disposal site assumes downward flow from the repository to the uppermost aquifer, an extensive unsaturated zone, low groundwater availability, and a very deep aquifer. Potential groundwater releases to the accessible environment are modeled through the uppermost aquifer, located about 200 meters below the repository.

Potential Near-Surface Intrusion Events. The potential near surface intrusion events are the intruder drilling, intruder agricultural, and intruder construction scenarios. Drilling, if it occurs, is likely to penetrate the waste zone at all near-surface disposal facilities, independent of the waste form, engineered barrier, or disposal depth. The use of monuments, barriers, or markers can reduce, but not preclude, the likelihood of drilling into the waste disposal area. The volume of radioactive material brought to the surface during a drilling operation is a function of the drill core diameter, the proximity to the waste form (fraction hit/not hit), the thickness of the waste form and the time after disposal that drilling occurs. The intruder agriculture and intruder construction scenarios are also possible at all near-surface disposal facilities. The impacts of these scenarios vary primarily as a function of when they occur and the extent to which they occur. Default values used in the GTCC LLW intruder analyses were taken from NRC accepted default parameters and values.

The five near-surface disposal concepts considered for all types of inadvertent intrusion are: aboveground vaults with no cover, earth-mounded vaults, belowground vaults, modular concrete canisters, and shallow-land disposal.

- Walking over the site or on-site exploration
- Constructing a home at the site
- Drilling and using a water well on-site
- Growing a garden or other foodstuffs on-site.

The consequences to the inadvertent intruder of one or several of these events occurring might take the form of

- Inhalation of radioactive waste mixed with soil from on-site excavation or drilling
- Direct gamma exposure from constructing a home on-site
- Ingestion of contaminated water from drilling a well on-site
- Ingestion of contaminated foodstuffs grown on-site.

Inadvertent intrusion events and pathways are grouped and discussed as three scenarios: (a) intruder-drilling/resource mining/mineral exploration, (b) intruder construction, and (c) intruder agricultural.

Intruder Drilling/Resource Mining/Mineral Exploration Scenario. Drilling and mining operations take place at or near the disposal facility after institutional control is lost. Mining or drilling exploratory wells for resources such as water, minerals, oil, and gas, or drilling exploratory wells as part of development or characterization of a new facility occur. The drillholes penetrate the waste and bring contamination to the surface.

Intruder Construction Scenario. The intruder constructs a house on the disposal facility. It is assumed that the intruder contacts radioactive wastes while performing the necessary excavation work to construct a basement for a house. The construction work is assumed to last for 500 hours; a conventional home construction period.

high level waste (EPA 1985) suggest that this is of negligible importance compared with the direct release to the surface.

Consequence of Potential Intrusion Events. The drilling intrusion scenario consequence analysis was conducted with the EPA's REPRISK code (Smith, 1982). The intruder agriculture and intruder construction scenarios were also conducted with the REPRISK code. REPRISK reports the total expected health effects to the population over the 100,000-year analysis period.

A drilling intrusion scenario analysis was conducted for each possible disposal site where the probability of its occurrence was likely. The most conservative parameters for each hypothetical disposal facility were utilized to conduct one worst case analysis for each disposal facility where drilling might occur. The potential for disruption of the base-case conditions by a drilling intrusion event was analyzed using event trees (Merrell, 1993). Intrusion events are characterized by the probability of the event and recurrence rate. Drilling and hitting a waste form is consider distinct from drilling and not hitting a waste form. The values used in REPRISK for a hypothetical disposal facility at an arid and humid site are shown in Figures 5-9 and 5-10. These event trees show the likelihood of disruptive drilling intrusions that could occur at the disposal facility. For each event shown in the tree, an annual recurrence rate was obtained from available data (EPA 82). From this recurrence rate, the probability of an event occurring over 100,000 years was calculated. The probability of an event not occurring in that time frame is complementary to the probability of the occurrence. A drill hole diameter of ten inches and a waste package hit fraction of fifteen percent was used for all drilling intrusion analyses. In addition the drilling intruder analysis addressed four other critical parameters. These are the likelihood of multiple boreholes, the no-hit event, the direct hit event, and the artificial pathway created by borehole intrusion. Each is discussed in the following paragraphs, but it is noted that the parameters were consistent across disposal facility concepts such that no undue weight would be given to one disposal concept over another.

Multiple boreholes will be drilled having the possibility that some boreholes will intersect the waste and others may not (EPA 1982 and EPA 1985). The possibility also exists of a fractional intersection of the waste. Drilling operations penetrate GTCC LLW at the disposal facility depending on the condition of the waste container and the waste. In the event the radioactive waste package is penetrated, GTCC LLW radioactive waste will be brought to the surface.

The no-hit drilling event occurs when waste containers are not penetrated. Drill tailings and groundwater brought to the surface will be contaminated by radioactivity that has been released from the

The drilling intrusion scenario is likely for: belowground vaults, modular concrete canisters, and shallow-land disposal concepts. These disposal sites will look very ordinary to exploratory drillers and miners. After institutional controls are vacated, the surface horizon will not show any indication of what is just a few meters below. It is assumed that GTCC LLW deposited on the surface horizon (e.g., aboveground vaults or earth-mounded vaults) will present a natural and obvious deterrent to exploratory drillers and miners and they will not start drilling operations on large mounded surfaces.

The intruder agriculture and intruder construction scenarios are considered only likely to occur for aboveground vaults with no cover and earth-mounded vaults disposal concepts. These intrusive events are not likely to occur for the other near-surface disposal concepts as a result of the cover depth over the waste packages and the fact that the waste is below natural grade. Excessive erosion of the cover might make the waste accessible in the long-term future, but the consequence to the intruder would be considerably diminished as a result of radioactive decay of the GTCC LLW. In this case the intruder agriculture and intruder construction scenarios would be comparable to those expected for the aboveground vault and earth-mounded vaults far into the future.

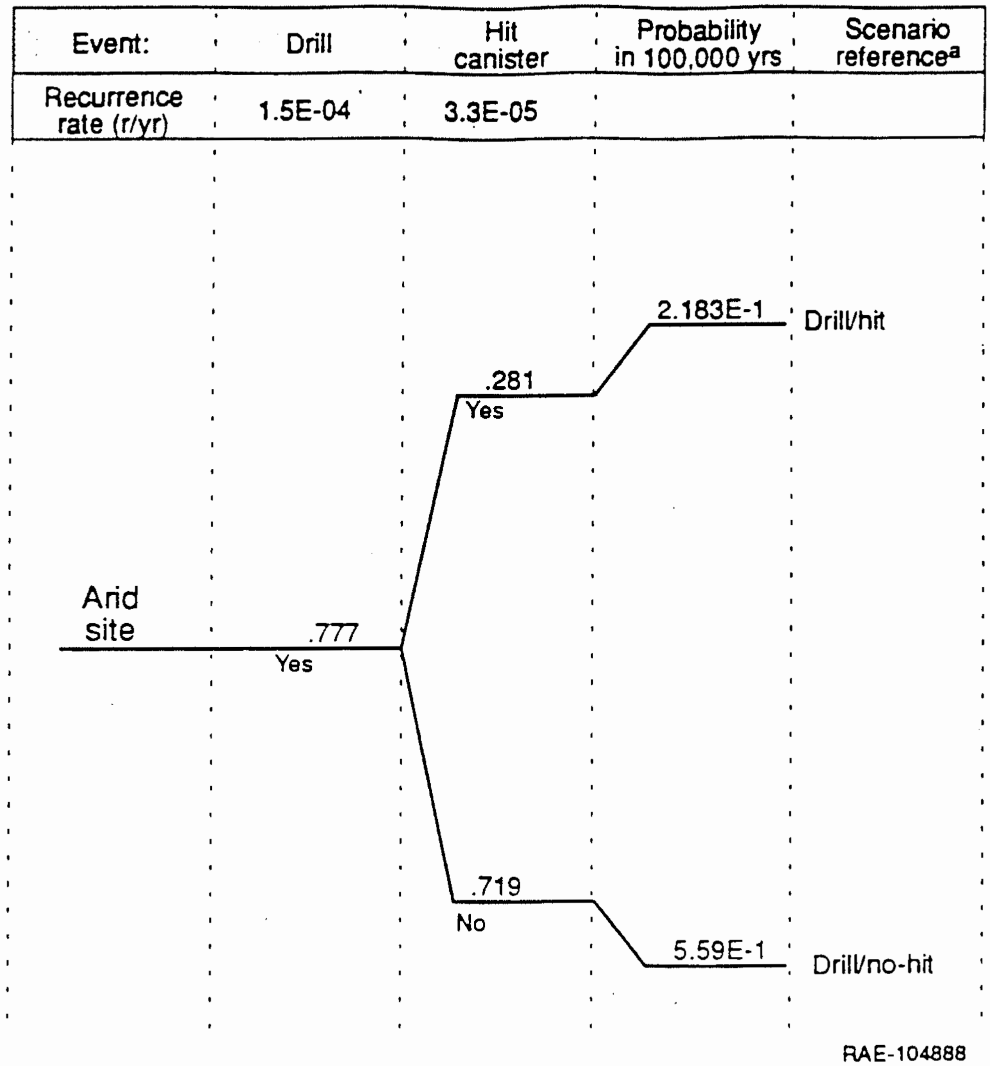
Potential Intermediate-Depth and Deep Geologic Intrusion Events. The only potential intrusive event into an intermediate-depth or deep geologic disposal facility is an intrusive drilling event. Other intrusive events (intruder agriculture and intruder construction) are discarded due to the inaccessibility of the waste packages. The two intermediate-depth and deep geologic disposal concepts considered for inadvertent intrusion are the drilled hole and mined cavity. The areal extent of the disposal facility, or "footprint," of the intermediate-depth and deep geologic disposal concepts is an important consideration in intrusion due to drilling. Drilling is likely to penetrate the waste zone at some points in the intermediate-depth and deep geologic disposal facilities, independent of the waste form, engineered barrier, or disposal depth. The use of monuments, barriers, or markers can reduce, but not preclude, the likelihood of drilling into the waste disposal area. The volume of radioactive material brought to the surface during a drilling operation is a function of the drill core diameter, the proximity to the waste form (fraction hit/not hit), the thickness of the waste form and the time after disposal that drilling occurs. Some of the future drillholes might intersect actual waste canisters, bringing a portion of their contents to the surface. Other drillholes will not intersect the waste packages themselves, but may bring contaminated drill cuttings and ground water to the surface. It is also possible that in abandoning such future boreholes, a more permeable pathway might be established between the disposal horizon and the overlying or underlying aquifers. Calculations that have been carried out for drill/hit scenarios with

Table 5-50. Estimated consequence of intrusion events at a humid site.

Disposal facility	Intrusion scenario	Health effects per 100,000 years[a]	Dominant radionuclides
Aboveground vault			
	Drill/hit	(b)	-
	Drill/no hit	(b)	-
	Intruder agriculture	207	Pu-239, C-14, Am-241
	Intruder construction	35,400	Pu-239, Co-60, Cs-137, Nb-94
Earth-mounded vault			
	Drill/hit	(b)	-
	Drill/no hit	(b)	-
	Intruder agriculture	207	Pu-239, C-14, Am-241
	Intruder construction	17,800	Pu-239, Co-60, Cs-137, Nb-94
Belowground vault			
	Drill/hit	6.3	Pu-239
	Drill/no hit	3.4	Pu-239, C-14, Ni-59, Tc-99
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Modular concrete canister			
	Drill/hit	6.3	Pu-239
	Drill/no hit	1.2	Pu-239, C-14, Ni-59
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Shallow-land disposal			
	Drill/hit	6.3	Pu-239
	Drill/no hit	5.9	Pu-239, C-14, Ni-59
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Mined cavity			
	Drill/hit	6.3	Pu-239
	Drill/no hit	1.5	Pu-239, C-14
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Drilled hole			
	Drill/hit	6.3	Pu-239
	Drill/no hit	0.85	C-14
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-

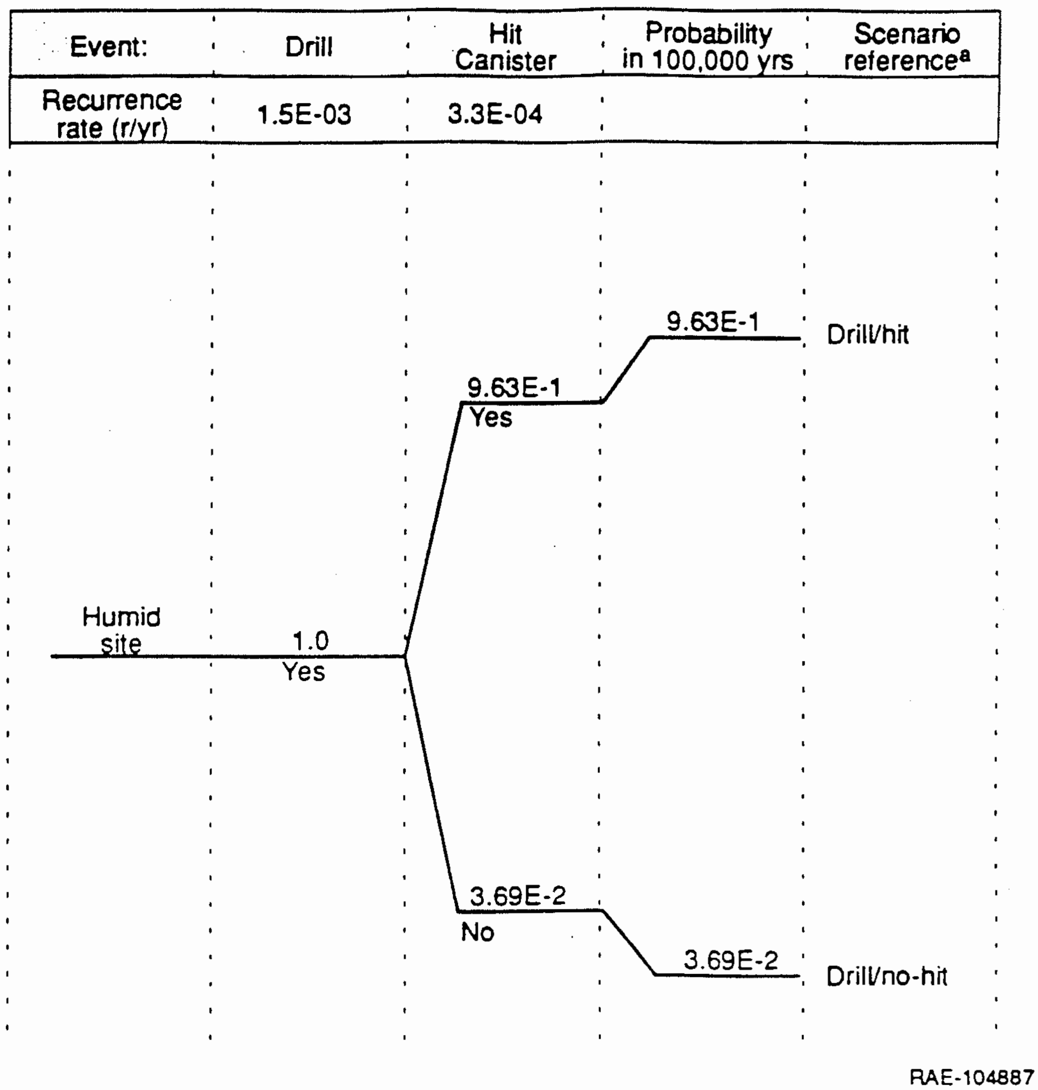
a. Most conservative estimate.

b. No intrusion scenario.



[a]Disruptive events include normal groundwater flow.

Figure 5-9. Event tree for the disposal facility at an arid site.



[a]Disruptive events include normal groundwater flow.

Figure 5-10. Event tree for the disposal facility at a humid site.

Table 5-51. Estimated consequence of intrusion events at an arid site.

Disposal facility	Intrusion scenario	Health effects per 100,000 years[a]	Dominant radionuclides
Aboveground vault			
	Drill/hit	(b)	-
	Drill/no hit	(b)	-
	Intruder agriculture	205	Pu-239, C-14, Am-241
	Intruder construction	35,400	Pu-239, Co-60, Cs-137, Nb-94
Earth-mounded vault			
	Drill/hit	(b)	-
	Drill/no hit	(b)	-
	Intruder agriculture	205	Pu-239, C-14, Am-241
	Intruder construction	17,800	Pu-239, Co-60, Cs-137, Nb-94
Belowground vault			
	Drill/hit	6.2	Pu-239
	Drill/no hit	0.9	Pu-239, C-14, Ni-59, Tc-99
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Modular concrete canister			
	Drill/hit	6.2	Pu-239
	Drill/no hit	0.3	Pu-239, C-14, Ni-59
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Shallow-land disposal			
	Drill/hit	6.2	Pu-239
	Drill/no hit	1.5	Pu-239, C-14, Ni-59
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Mined cavity			
	Drill/hit	6.2	Pu-239
	Drill/no hit	0.2	Pu-239, C-14
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-
Drilled hole			
	Drill/hit	6.2	Pu-239
	Drill/no hit	0.3	C-14
	Intruder agriculture	(b)	-
	Intruder construction	(b)	-

a. Most conservative estimate.

b. No intrusion scenario.

scenario were adapted from those found in (NRC 1981) and (Oztunali 1986). It is important to note that the NRC assumes that the time delay from burial to excavation for this scenario is 500 years, longer than the 100 year institutional control period. The pathways simulated from this type of intrusion scenario are inhalation of air contaminated by the resuspended radioactive waste, ingestion of food grown in the contaminated soil and irrigated with contaminated water, and ingestion of contaminated water. Appropriate equations for pathway analysis are given in (Smith 1982). The limiting dose criterion from this type of intrusion scenario is a total effective dose of 100 mrem, as stated in (Kennedy 1988). In all pathways, the dose calculated exceeded this limit, translating to greater than acceptable health effects. The total dose to an individual was calculated using the PATHRAE-EPA code (EPA 1987). This dose over all pathways exceeded 40,000 mrem/yr at year 500 into the analysis for both disposal concepts considered.

Results from these REPRISK analyses are given in Tables 5-50 and 5-51. The results show that for the most conservative parameters considered for the two disposal facilities where the intrusion agriculture scenario might occur, that the humid sites consistently yielded the highest reported health effects over the 100,000-year analysis period. The number of reported health effects for ingestion of food and water and the inhalation of dust pathway was 207 for the two sites considered. The arid disposal facilities had slightly lower reported health effects for all of the disposal facility sites considered as shown in Table 5-51. The primary radionuclides contributing to reported health effects were Pu-239, C-14, and Am-241 for both the ingestion of food and water and inhalation of dust pathways.

An intruder construction scenario analysis was conducted for each possible disposal site where the probability of its occurrence was likely. The two most likely disposal facilities are the above ground vault and earth mounded vault disposal sites. Pathway parameter values used for the analysis of this intrusion scenario were adapted from those found in (NRC 1981) and (Oztunali 1986). The NRC assumes that the time delay from burial to excavation for this scenario is 500 years, longer than the 100-year institutional control period. The pathways simulated from this type of intrusion scenario are inhalation of air contaminated by the mixture of resuspended radioactive waste and soil and direct exposure to gamma radiation. Appropriate equations for pathway analysis are given in (Smith 1982). The limiting dose criterion from this type of intrusion scenario is a total effective dose of 500 mrem, as stated in (Kennedy 1988). In all pathways, the dose calculated exceeded this limit, translating to greater than acceptable health effects. The total dose to an individual was calculated using the PATHRAE-EPA code. The dose calculated from the direct gamma and on-site inhalation pathway exceeded 10,000 mrem/yr at year 500 into the analysis for both disposal concepts considered.

Results from these REPRISK analyses are given in Tables 5-50 and 5-51. The results show that for the most conservative parameters considered for the two disposal facilities where the intrusion construction scenario might occur, that the humid sites consistently yielded the highest reported health effects over the 100,000-year analysis period. The number of reported health effects for ingestion of food and water, inhalation of dust, and direct gamma pathway was 17,800 for the earth mounded vault disposal concept and 35,400 for the above ground vault with no cover. The arid disposal facilities had slightly lower reported health effects for all of the disposal facility sites considered as shown in Table 5-51. The primary radionuclides effecting the reported health effect were Pu-239, C-14 and Am-241 for the inhalation of dust pathway. Pu-239, Co-60, Cs-137, and Nb-94 were the major contributors to the overall health effect reported for the direct gamma pathway.

5.4 Summary of Disposal Concept Performance

Each of the 13 disposal concepts was evaluated in terms of three measures of confinement and two intrusion measures in Section 5.3. Each disposal concept was evaluated for disposal of each of four waste categories and a composite of all GTCC LLW. The results for the 13 disposal concepts are summarized in this section.

5.4.1 Summary of Confinement Performance

The results calculated for each disposal concept in terms of the three confinement performance measures, total release, groundwater concentration, and radiation dose, are summarized in Tables 5-52, 5-53, and 5-54, respectively. Throughout these three tables a value inside a box designates the best performance within each column. A value that is in a box and is shaded designates the best performance for a particular waste category.

As shown in Table 5-52, with the exception of near-surface shallow-land disposal and modular concrete canisters and intermediate-depth and deep geologic concepts using high-integrity containers, all the disposal concepts result in equal total releases from activated metals. For the other three categories of GTCC LLW, arid site near-surface vaults result in the lowest total releases. Overall, if all GTCC LLW were disposed in the same disposal concept, then arid near-surface aboveground, belowground, or earth-mounded concrete vaults result in the lowest total releases. These total releases are 46% less than the lowest releases from intermediate-depth or deep geologic disposal concepts.

Table 5-52. Summary of total release measure.

	Activated metals		Process waste		Contaminated equipment and material		Sealed Sources		All GTCC LLW	
	Arid	Humid	Arid	Humid	Arid	Humid	Arid	Humid	Arid	Humid
Near-surface										
Shallow-land disposal	0.16	0.16	0.12	0.34	23.00	48.78	67.07	73.17	20.41	22.26
Modular concrete canisters	0.16	0.16	0.07	0.12	10.80	31.36	39.02	73.17	11.92	22.25
Earth-mounded vaults	0.15	0.15	0.05	0.08	6.97	17.07	26.83	73.17	8.22	22.24
Belowground vaults	0.15	0.15	0.05	0.07	6.62	16.38	26.83	73.17	8.22	22.24
Aboveground vaults	0.15	0.15	0.05	0.07	6.62	16.38	26.83	73.17	8.22	22.24
Intermediate-depth										
Drilled hole/high-integrity container	0.16	0.15	0.09	0.11	13.45	26.55	40.00	75.00	12.07	22.43
Drilled hole/high-level-waste type container	0.15	0.15	0.06	0.09	10.34	22.07	40.00	75.00	12.07	22.43
Miner cavity/high-integrity container	0.16	0.15	0.08	0.11	12.41	26.90	40.63	75.00	12.26	22.54
Mined cavity/high-level-waste type container	0.15	0.15	0.06	0.09	10.00	22.07	40.00	75.00	11.97	22.54
Deep geologic										
Drilled hole/high-integrity container	0.16	0.15	0.09	0.11	13.45	26.55	40.00	75.00	12.07	22.43
Drilled hole/high-level-waste type container	0.15	0.15	0.06	0.09	10.34	22.41	40.00	75.00	12.07	22.43
Mined cavity/high-integrity container	0.16	0.15	0.08	0.11	12.41	26.90	40.00	75.00	12.07	22.54
Mined cavity/high-level-waste type container	0.15	0.15	0.06	0.09	10.00	22.07	40.00	75.00	12.07	22.54

Table 5-53. Summary of peak groundwater concentration measure (Ci/ft^3).

	Activated metals		Process waste		Contaminated equipment and material		Sealed Sources	
	Arid	Humid	Arid	Humid	Arid	Humid	Arid	Humid
Near-surface								
Shallow-land disposal	1.4E-06	5.3E-02	5.7E-07	7.6E-04	---	2.3E-03	---	4.0E+02
Modular concrete canisters	8.3E-07	5.3E-02	9.5E-07	9.7E-04	---	2.8E-03	---	1.5E+02
Earth-mounded vaults	8.0E-07	2.4E-02	3.0E-07	4.9E-03	---	3.0E-03	---	2.6E+00
Belowground vaults	8.1E-07	4.9E-02	2.8E-07	5.2E-03	---	6.7E-03	---	5.1E+01
Aboveground vaults	4.6E-08	2.5E-02	2.8E-07	1.6E-03	---	4.2E-04	---	2.5E+01
Intermediate-depth								
Drilled hole/high-integrity container	3.0E-07	1.2E-04	3.0E+02	3.3E-05	---	---	---	---
Drilled hole/high-level-waste type container	3.8E-07	1.2E-04	9.6E-08	2.5E-05	---	---	---	---
Miner cavity/high-integrity container	5.7E-07	3.1E-04	1.3E-07	8.5E-05	---	---	---	---
Mined cavity/high-level-waste type container	5.5E-07	2.8E-04	1.9E-07	7.1E-05	---	---	---	---
Deep geologic								
Drilled hole/high-integrity container	1.3E-05	7.4E-06	1.7E-06	7.4E-07	---	---	---	---
Drilled hole/high-level-waste type container	1.2E-05	7.4E-06	4.1E-06	3.0E-06	---	---	---	---
Mined cavity/high-integrity container	9.9E-06	1.9E-05	1.8E-06	1.9E-06	---	---	---	---
Mined cavity/high-level-waste type container	8.8E-06	1.9E-05	2.5E-06	1.7E-06	---	---	---	---

Table 5-54. Summary of peak radiation dose measure (mrem/yr).

	Activated metals		Process waste		Contaminated equipment and material		Sealed Sources	
	Arid	Humid	Arid	Humid	Arid	Humid	Arid	Humid
Near-surface								
Shallow-land disposal	2.4E+02	8.8E+05	4.1E+03	8.4E+07	---	2.5E+08	---	4.4E+13
Modular concrete canisters	2.2E+02	8.8E+05	6.7E+03	1.0E+08	---	3.1E+08	---	1.6E+13
Earth-mounded vaults	2.0E+02	5.6E+05	2.2E+03	1.6E+07	---	3.3E+08	---	2.8E+11
Belowground vaults	2.1E+02	6.4E+05	2.0E+03	2.5E+08	---	7.4E+08	---	5.6E+12
Aboveground vaults	1.7E+02	5.6E+05	2.0E+03	1.8E+08	---	4.6E+07	---	2.7E+12
Intermediate-depth								
Drilled hole/high-integrity container	5.1E+01	5.3E+03	2.7E+02	5.7E+03	---	---	---	---
Drilled hole/high-level-waste type container	5.3E+01	4.8E+03	4.9E+02	3.5E+03	---	---	---	---
Miner cavity/high-integrity container	1.0E+02	1.4E+04	9.3E+02	1.4E+04	---	---	---	---
Mined cavity/high-level-waste type container	1.0E+02	1.2E+04	1.3E+03	1.2E+04	---	---	---	---
Deep geologic								
Drilled hole/high-integrity container	6.0E+02	3.6E+02	8.7E+02	1.8E+03	---	---	---	---
Drilled hole/high-level-waste type container	5.7E+02	3.7E+02	1.6E+03	1.0E+03	---	---	---	---
Mined cavity/high-integrity container	4.9E+02	9.4E+02	2.4E+03	4.6E+03	---	---	---	---
Mined cavity/high-level-waste type container	4.4E+02	9.5E+02	2.7E+03	2.5E+03	---	---	---	---

Table 5-53 summarizes the peak radionuclide concentrations in the groundwater for those disposal concepts where such contamination occurs within the 100,000-year simulation period. The activated metals, near-surface concepts, intermediate-depth disposal concepts, and deep geologic mined cavity concepts result in groundwater concentration that is within a factor of 10 of each other. Of these concepts the abovegrade vault results in the lowest peak groundwater concentration. A similar relationship exists between the concepts when process waste is disposed of. All groundwater concentrations are within a factor of 10 of each other, with intermediate-depth drilled holes using high-level-waste type containers resulting in the lowest peak groundwater concentration. For contaminated equipment and material and sealed sources all of the concepts, if used at the arid site, and all of the intermediate depth or deep geologic concepts at the humid site do not result in any groundwater contamination within the 100,000-year simulation period.

Table 5-54 summarizes the peak radiation dose resulting from consumption of contaminated groundwater. As shown, the intermediate-depth and deep geologic concepts result in radiation doses from activated metals that are one to three orders-of-magnitude less than the doses for the near-surface concepts at the humid site. At the arid site the radiation doses are about equal for all the disposal concepts, except for intermediate-depth drilled holes which are about an order-of-magnitude less. The disposal concepts rank in approximately the same order when the process waste category is considered. For contaminated equipment and material and sealed sources all concepts, when used at the arid site, and the humid site intermediate-depth and deep geologic concepts result in no radiation dose.

5.4.2 Summary of Intrusion Performance

Intrusion was measured in both qualitative and quantitative terms. Table 5-55 summarizes the qualitative and quantitative results for all the GTCC LLW disposal concepts. As shown, each concept is judged to be susceptible to only two of the four potential intrusion events. The near-surface abovegrade and earth-mounded vaults are susceptible to intrusion under the intruder agriculture and intruder construction scenarios and not from either drilling scenario. The remaining near-surface and all the intermediate-depth and deep geologic disposal concepts are only susceptible to the two drilling scenarios.

In Table 5-55, a value inside a box denotes the best performance in that column. A value inside a box that is also shaded denotes the disposal concept having the best intrusion performance. Under the intruder agriculture scenario the near-surface abovegrade and earth-mounded vaults produce identical results. Under the intruder construction scenario the earth-mounded vault results in 50% fewer health

Table 5-55. Summary of intrusion measures.

	Potential intrusion scenarios and health effects							
	Drill/hit		Drill/no hit		Intruder Agriculture		Intruder Construction	
	Possible	Health effects per 100,000 years	Possible	Health effects per 100,000 years	Possible	Health effects per 100,000 years	Possible	Health effects per 100,000 years
Shallow-land disposal								
Arid	Yes	6.2	Yes	1.5	No	---	No	---
Humid	Yes	6.3	Yes	5.9	No	---	No	---
Modular concrete canister								
Arid	Yes	6.2	Yes	0.3	No	---	No	---
Humid	Yes	6.3	Yes	3.4	No	---	No	---
Aboveground vault								
Arid	No	---	No	---	Yes	205	Yes	35,400
Humid	No	---	No	---	Yes	207	Yes	35,400
Belowground vault								
Arid	Yes	6.2	Yes	0.9	No	---	No	---
Humid	Yes	6.3	Yes	3.4	No	---	No	---
Earth-mounded vault								
Arid	No	---	No	---	Yes	205	Yes	17,800
Humid	No	---	No	---	Yes	207	Yes	17,800
Mined cavity								
Arid	Yes	6.2	Yes	0.2	No	---	No	---
Humid	Yes	6.3	Yes	1.5	No	---	No	---
Drilled hole								
Arid	Yes	6.2	Yes	0.3	No	---	No	---
Humid	Yes	6.3	Yes	0.85	No	---	No	---

effects. Under the drill/hit scenario the three near-surface belowground concepts and the intermediate-depth and deep geologic concepts perform equally well. However, under the drill/no hit scenario the mined cavity results in the lowest number of potential health effects.

6. IDENTIFICATION OF RECOMMENDED DISPOSAL CONCEPTS

The probabilistic performance assessments of the GTCC LLW disposal concepts provided relative measures of concept performance based on their ability to confine disposed of radioactivity and to minimize exposures to inadvertent intruders. These preliminary results are used to recommend the disposal concept(s) that are most effective in meeting performance objectives and those that represent the most technically desirable alternative(s) for the disposal of GTCC LLW.

The confinement and intrusion performance measures allow identification of the most effective concept for a given category of waste and disposal site. These individual measures must be combined to identify the concept(s) that are most effective in meeting all of the various performance measures. The criteria developed to examine the total performance of each concept, and used in the identification of the recommended GTCC LLW disposal concept(s), are discussed in Section 6.1. Recommended disposal concepts are reported in Section 6.2.

6.1 Selection Criteria

The use of several confinement and intrusion performance measures to judge the effectiveness of the GTCC LLW disposal concepts complicates the process of selecting the most effective alternative(s). While some of the measures are directly proportional to one another, for example groundwater concentration and dose to the off-site individual, others may not share this commonality. Performance measures for confinement and intrusion gauge very divergent aspects of concept performance.

Because of the complex and varied relationships between the confinement and intrusion performance measures, it is imperative to weight the measures based on their relative importance. A key aspect of the selection process used in identifying the recommended GTCC LLW disposal concept(s) concerns the nature of this weighting process, specifically whether all five performance measures (three for containment and two for intrusion) are given equal weight.

The performance measures for confinement were set by considering the total release of radioactivity from the disposal concepts, the groundwater concentrations resulting from these releases, and the doses to an individual consuming contaminated groundwater. The amount of radioactivity released from the facility will be relatively less important than the latter two performance measures over a given simulation period; radionuclides released from the waste that do not reach the groundwater during this time are unable to impact groundwater resources or result in potential health effects to users of the groundwater.

Based on this assessment, the confinement measure of relative health impacts was assigned greater importance in concept rankings. If two or more concepts were judged to be similar based on this measure, or if there were no projected adverse health effects, the effectiveness of the concepts in limiting the release of radioactivity to the environment was considered.

The intrusion performance measures must also be taken into account in selecting the most effective GTCC LLW disposal concept(s). The measure of relative adverse health effects to the inadvertent intrusion was considered to have the same degree of importance as the relative health impact confinement measure. If no health impacts resulted from intrusion, this aspect of concept performance was not considered in ranking the disposal concepts.

The effectiveness of the GTCC LLW disposal concepts vary with the category of waste and the site at which the disposal concept is located. To account for these potential variations, the selection criteria were applied to the individual waste types for each concept at each site. In addition, the disposal concepts were ranked based on their effectiveness for the situation where all GTCC LLW was disposed of in the same concept.

6.2 Recommended Disposal Concepts

The disposal concept recommendations based on the selection criteria discussed in Section 6.1 are provided in the following subsections. The recommended concepts for the arid site are discussed in Section 6.2.1, while recommendations for the humid site are addressed in Section 6.2.2.

6.2.1 Arid Site Concept Recommendations

Two of the near-surface GTCC LLW disposal concepts at the arid site, abovegrade vault and earth-mounded vault, were eliminated from further consideration based on their relative intruder health effects performance measure (see Table 5-59). Projected health effects for these concepts are orders-of-magnitude greater than those for all other disposal concepts. Of the remaining arid site concepts the intermediate-depth or deep geologic mined cavity results in the lowest number of total potential health effects (across all applicable scenarios). The intermediate-depth or deep geologic drilled hole concepts and the near-surface modular concrete canister concept result in potential health effects that are only 0.1 greater (less than a 2% increase over the health effects for the mined cavities.)

Based on performance against the radiation dose measure (see Table 5-58), all of the near-surface, intermediate-depth and deep geologic concepts if used at the arid site perform equally well. Radiation doses from intermediate-depth concepts are about a factor of 2 to 6 less than those for either near-surface or deep geologic.

Examination of total release (Table - 5-56) and groundwater concentration (Table 5-57) shows that the near-surface concepts will result in the lowest total release. The resulting groundwater concentrations are about equal to those for the intermediate-depth and deep geologic concepts.

The recommended arid site disposal concepts are based on performance in terms of intrusion and radiation dose. The intrusion and radiation dose performance is considered to be equal for the intermediate-depth drilled holes and mined cavity concepts and for the near-surface modular concrete canisters. Deep geologic concepts are not recommended due to their higher potential radiation doses for activated metals and process waste.

6.2.2 Humid Site Concept Recommendations

Similar to the situation seen for the arid site, the abovegrade vault and earth-mounded vault disposal concepts were eliminated from further consideration at the humid site based on their relative intruder health effects performance measure (see Table 5-59). Projected health effects for these concepts are close to four orders of magnitude greater than those for all other disposal concepts. Of the remaining humid site concepts the intermediate-depth and deep geologic drilled hole concepts result in the lowest total potential health effects (7.15 per 100,000 years). Mined cavities are slightly higher at 7.8 while the results for the remaining near-surface concepts are 9.7 for modular concrete canisters and belowground vaults and 12.2 for shallow-land disposal.

Based on performance against the radiation dose measure (Table 5-56) the deep geologic concepts produce the lowest peak doses. The intermediate-depth concepts are typically either a factor of 10 while the near-surface concepts result in peak doses that are four to five orders of magnitude higher.

As in the arid site case, the near-surface concepts result in the lowest total releases. However, for all categories of GCC LLW the near-surface concepts result in the highest groundwater concentration at the humid site.

The recommended humid site disposal concepts are based on intrusion and radiation dose performances. The intrusion performance for the intermediate-depth and deep geologic concepts are considered equal and about 30% better than that for modular concrete canisters and belowground vaults. However, none of the near-surface disposal concepts are not recommended because of their high radiation doses. These doses are three to five orders-of-magnitude higher than those for the deep geologic disposal concepts. The recommended humid site concepts are, therefore, restricted to intermediate-depth or deep geologic drilled holes or mined cavities.

7. COST IMPLICATIONS FOR THE RECOMMENDED DISPOSAL SYSTEMS

A preliminary activity to the planned economic evaluation (block 1c in Figure 2-3 presented in Chapter 2) is the development of order-of-magnitude cost estimates. The purpose of Section 7 is to describe the methodology, assumptions, and data used to develop an order-of-magnitude cost estimate for each of the recommended disposal systems.

7.1 Cost Estimating Methodology

Development of the order-of-magnitude costs was initiated before the concepts of the recommended disposal systems were identified. An order-of-magnitude cost estimate was developed for nine of the 13 disposal concepts. The cost estimates do not consider cost of the high-integrity containers or high-level-waste type containers. From a cost estimating standpoint, there are, therefore, only two intermediate-depth and two deep geologic concepts to be considered; specifically a drilled hole and mined cavity concept at each depth. The order-of-magnitude cost estimate for the recommended disposal systems was prepared by combining cost estimates for the appropriate concepts making up the recommended disposal systems and then removing duplicative costs.

Existing cost data and cost estimates for similar radioactive waste management facilities are the basis for order-of-magnitude cost estimates for each of the nine disposal concepts. The life of a GTCC LLW disposal facility, starting with site selection and ending with postclosure care, was divided into eight phases as follows:

- Site selection
- Site characterization
- Environmental impact statement, licensing, and permitting
- Engineering design
- Construction
- Operations
- Closure

- 100 year postclosure care.

Cost data were assembled from a range of sources for each major cost component within each of these eight phases. Figure 7-1 shows the component costs for each phase in a disposal facility's life cycle. As shown, several phases can be pursued simultaneously while others must follow in sequence. Cost components were examined to determine the type of estimate used for estimating each GTCC LLW disposal concept. Types of cost estimates considered were as follows:

- Quantity-based estimates
- Scaled estimates
- Experience-based estimates.

Quantity-based estimates are the most direct and involved calculations and are based on available design information. For example, it is possible to calculate the total quantity of material to be excavated using design information. The cost of excavation can be estimated by multiplying this estimated quantity by a cost per unit volume (i.e., unit cost). Specifically, if the design indicates that 10,000 cubic yards (cy) of rock will be excavated from a shaft or hole and the unit cost of such excavation is $56/cy, the cost of the excavation would be $560,000. Quantity estimates can be used for estimating the cost of environmental monitoring, facility excavation, disposal unit construction, site work force, and operating equipment.

The second method of estimating costs uses scaling relationships. The cost of a component is estimated as some fraction of a related component, whose cost and characteristics are known. The known cost of the reference component is appropriately scaled based on the characteristics of the component whose cost is being estimated. For example, the cost of engineering and design services is estimated as 12% of the cost of constructing the support facilities, plus 3% of the cost of constructing the disposal units, plus 1% of the precharacterization and characterization costs. Scaled estimates can also be used for consumables and building maintenance.

The final type of cost estimate is experienced-based cost estimates. This type of estimate is used when quantitative information necessary to use one of the other two cost estimating methods is deficient. Experienced-based cost estimating makes use of unit costs or scaling factors, and combines them in a manner based on engineering judgment and experience. The cost for screening and selecting a site for

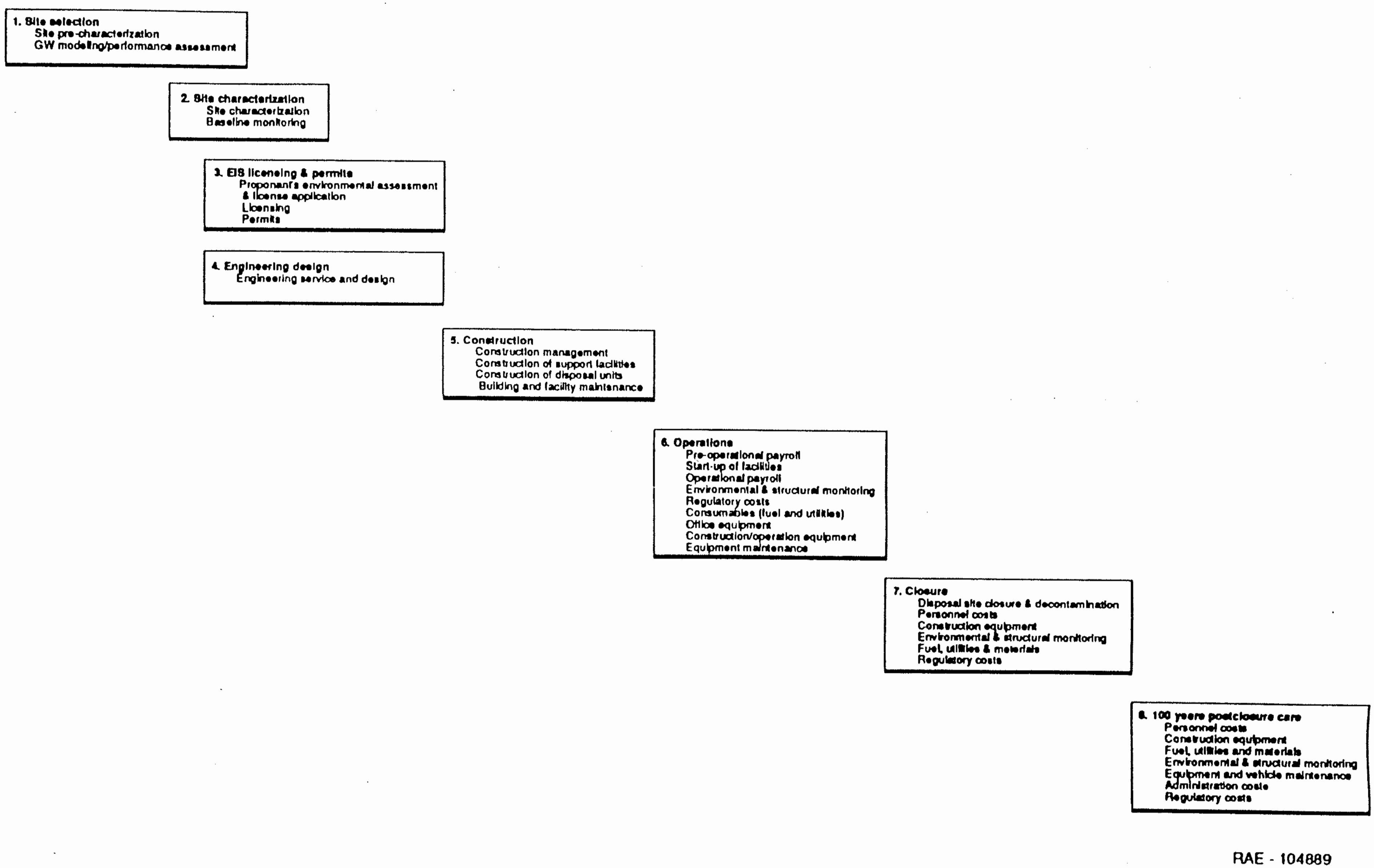


Figure 7-1. Component costs for each phase in a disposal facility lifecycle.

a GTCC LLW facility may be based on experience with similar activities for new LLW facilities. Specifically, if the cost of selecting a similar site is known to take two years at $5,000,000, it might be judged that the site selection process for a GTCC LLW facility would require twice as much information, and would require twice as much effort to collect because of the greater depths of the disposal horizon; therefore taking a period of four years. The cost of site selection for the GTCC LLW facility could be estimated to be $20,000,000. Experienced-based estimates might be applied to estimate the cost of groundwater modeling, performance assessment, and preparation of licensing, permitting, and environmental documents.

Once assembled, the cost component data were adjusted using a two-step process to arrive at GTCC LLW concept-specific cost estimates. First, the cost components were categorized as being fixed or variable. Fixed costs do not vary between disposal concepts or the volume of waste being disposed of. Examples of fixed costs include site screening and development of the proponents license application. Secondly, each variable cost was identified.

An order-of-magnitude cost estimate was developed for disposal of each of the four categories of GTCC LLW (DOE/LLW-114) in each of the nine disposal concepts. Another estimate was developed for the disposal of all categories of GTCC LLW in each concept. Once the concepts comprising the recommended disposal system were identified, the appropriate concept order-of-magnitude cost estimates were combined and the duplicative cost components were subtracted out.

7.2 Cost Data and Assumptions

The order-of-magnitude cost estimates for the GTCC LLW disposal concepts are based on cost data assembled and used in several LLW studies developed by RAE and others. The following is a listing of current cost studies.

Cost studies for radioactive waste disposal.

Analysis of the Total Life Cycle Cost for the Civilian Radioactive Waste Management Program
Conceptual Design Report -- Concepts for Near-Surface Disposal of Low-Level Radioactive Waste Generated in Vermont
Estimate of Life Cycle Costs for Vermont Low-Level Radioactive Waste Disposal Facility
Design and Analysis of the Texas LLW Disposal Facility Using Modular Concrete Canisters for All Waste
Low-Level Radioactive Waste Disposal Facility Conceptual Designs
Conceptual Design Report Alternative Concepts for Low-Level Radioactive Waste Disposal
Unit Costs and Quantities Used in Estimating Costs in the Conceptual Design Report
Engineering Cost Analyses for the Earth Mounded Concrete Bunker and Canister Disposal Methods and for the Engineered Surface Storage Method Applicable to Low-Level Waste Management.

Development of order-of-magnitude cost estimates involve considerable uncertainties associated with the use of hypothetical sites, the amount of GTCC LLW that any one concept would dispose of, the preliminary nature of the concept designs, and the lack of an established licensing process. The uncertainties require the use of several assumptions that are primarily related to either the development process; the facility size and components; or operations and post-operational conditions. The following are listings of the specific assumptions used.

Development process assumptions.

Facility development starts with the site screening process and continues through completion of facility construction
The facility development process will be completed in 10 years
DOE is the facility developer
Each concept, for cost estimating purposes only, is considered to be located at its own site (i.e., it is not collocated with another facility)
Labor and equipment to construct the support facilities and the disposal units are contracted.

Facility size and component assumptions.

A range of facility sizes are considered, ranging from a facility capable of disposing of all the GTCC LLW to one just large enough to dispose of the smallest waste category (i.e., contaminated equipment)

Each facility, regardless of size, includes all necessary support and infrastructure facilities to be a stand alone facility

A total of 3,250 m^3 (115,000 ft^3) of GTCC LLW will be disposed of

The facility operates for 20 years, receiving three license renewals and one amendment for facility closure

Disposal units are closed and covered or sealed, as appropriate, as each is filled to capacity

All near surface concepts use only high-integrity containers as the waste package

The cost of high-integrity containers and high-level waste type containers are not included in the cost estimate

The same size and shape high-integrity containers and high-level waste type containers are used, as appropriate in all disposal concepts

The cost to condition or treat GTCC LLW to fit in the high-integrity containers or high-level waste type containers is not included in the cost estimates.

Operational and post operational assumptions.

Each facility, regardless of size and capacity, operates 12 months a year

Total facility closure requires two years immediately following cessation of disposal operation

Institutional control starts immediately after facility closure and lasts for 100 years.

Assumptions that are not constrained to any one aspect or phase in the life cycle of the disposal facility are as follows:

- The capital cost of money was not included
- Constant 1992 dollars were used
- A 20% contingency is included in each cost component.

Development of cost estimates for four cost components required that engineering judgment and experience with the LLW and HLW disposal facility development processes be used. This judgment and experience was applied to develop multipliers that can convert costs based on the development of near-surface LLW disposal facilities into costs for near-surface, intermediate-depth, and deep geologic GTCC LLW facilities. The six cost components for which multipliers were developed are as follows:

- Site screening
- Site precharacterization
- Ground water modeling/performance assessment
- Site characterization
- Proponent's Environmental Assessment and license application
- Licensing.

Table 7-1 lists the multipliers used for each of these cost components. Each multiplier is based on engineering judgment and knowledge of how the costs associated with each cost component presently varies across the several LLW disposal facilities being developed. An additional cost related to the depth that well and characterization borings are drilled is included in the site precharacterization cost.

7.3 Order-of-Magnitude Costs by Disposal Concept

Using the methodology described in Section 7.1 and the data and assumptions discussed in Section 7.2, order-of-magnitude costs were developed. For each of the nine disposal concepts, five cost estimates were prepared. Each estimate is made up of cost components that were either constant for all disposal concepts, were constant for a particular concept regardless of the volume of waste being disposed of, or varied between concepts and with facility size. Table 7-2 indicates the cost estimating method used for each cost component.

Table 7-1. Cost component multipliers.

Cost component	Disposal horizon: Near-surface	Disposal horizon: Intermediate-depth	Disposal horizon: Deep geologic
Site screening	5	5	5
Site precharacterization	4	6	8
Ground water modeling/ performance assessment	4	6	10
Site characterization	4	10	25
Proponent's environmental assessment and license application	5	5	5
Licensing	4	6	10

Table 7-2. Cost estimating methods used.

	Cost components	Evaluation method
1)	Site selection	
	Site screening	Experience & scaling
	Site precharacterization	Experience & scaling
	GW modeling/performance assessment	Experience & scaling
2)	Site characterization	
	Site characterization	Experience & scaling
	Baseline monitoring	Quantity & experience
3)	EIS & licensing & permits	
	Proponent's environmental assessment & license application	Experience & scaling
	Licensing	Experience & scaling
	Permits.	Experience & scaling
4)	Engineering design	
	Engineering service and design	Scaling
5)	Construction	
	Construction management	Scaling
	Construction of support facilities	Quantity
	Construction of disposal units	Quantity
	Building and facility maintenance	Scaling
6)	Operations	
	Preoperation payroll	Quantity & scaling
	Startup of facilities	Scaling
	Operation payroll	Quantity & scaling
	Environmental & structural monitoring	Quantity & experience
	Regulatory costs	Experience & scaling
	Consumables (fuel and utilities)	Scaling
	Office equipment	Experience
	Construction/operation equipment	Quantity & scaling
	Equipment maintenance	Scaling
7)	Closure	
	Disposal site closure & decontamination	Quantity & scaling
	Personnel costs	Quantity & scaling
	Construction equipment	Quantity & scaling
	Environmental & structural monitoring	Quantity & experience
	Fuel, utilities & materials	Scaling
	Regulatory costs	Experience & scaling
8)	100 year postclosure care	
	Personnel costs	Quantity & scaling
	Construction equipment	Quantity & scaling
	Fuel, utilities and materials	Scaling
	Environmental & structural monitoring	Quantity & experience
	Equipment and vehicle maintenance	Scaling
	Administration costs	Experience
	Regulatory costs	Experience & scaling

7.3.1 Near-Surface Disposal Concept Costs

The total order-of-magnitude costs for the five near-surface GTCC LLW disposal concepts range from $129,000,000 for a shallow-land disposal facility for only one category of GTCC LLW to $211,000,000 for an earth-mounded vault disposing of all GTCC LLW. The corresponding per cubic meter costs range from $50,000 to $65,000. The shallow land disposal concept has the lowest cost, while the earth-mounded vault has the highest cost. The cost for the below ground vault concept is about 10% more than the cost for the shallow land disposal concept. The above ground vault and the modular concrete canister concepts have nearly the same costs and are about 17% more than the shallow land disposal cost. Table 7-3 summarizes and Figure 7-2 shows the spread between the total and per-cubic-meter costs for each near-surface concept having the capacity to dispose of all GTCC LLW.

Should the near surface concepts be used only to dispose of a portion of the GTCC LLW, costs will vary as shown in Figure 7-3. Total shallow-land disposal cost decreases from about $163,000,000 to about $129,000,000 , a 20% decrease. The total earth-mounded vault cost decreases by about 30%, from $211,000,000 to $148,000,000. Conversely, the per-cubic-meter costs increase by a factor of more than 10. The shallow land disposal per cubic meter cost increases from about $50,000 to about $645,000, while the same cost for the earth-mounded vault increases from $65,000 to over $730,000. The corresponding decreases in total cost and increases in the per cubic meter cost for the other three near-surface concepts are in the ranges shown in Figure 7-3.

Figure 7-4 shows total concept costs assigned to the eight phases in the life of a GTCC LLW concept. Values for the shallow-land disposal and earth-mounded vault concepts are shown, and the costs for the other near-surface concepts fall between the costs for these two concepts. The majority of the difference in cost among the five near-surface concepts is reflected in the costs for facility construction and closure. Smaller differences are found in the costs for design and engineering, operations, and postclosure care. The costs for site selection and characterization, licensing, permitting, and environmental documentation are the same for all five concepts. The estimated cost for each near-surface concept by phase and cost component is provided in Tables 7-4 through 7-8.

7.3.2 Intermediate-Depth Disposal Concept Costs

The total order-of-magnitude costs for the two intermediate-depth GTCC LLW disposal concepts range from $201,000,000 to $293,000,000. The corresponding per cubic meter cost ranges from $84,000

Table 7-3. Summary of near-surface disposal concept costs for disposal of all GTCC LLW.

Disposal Concept	Total Life Cycle Cost	Per Cubic Meter Cost
Shallow-land disposal	$162,595,000	$50,000
Belowground vault	$179,513,000	$55,000
Aboveground vault	$190,172,000	$58,000
Modular concrete canister	$190,702,000	$59,000
Earth-mounded vault	$210,680,000	$65,000

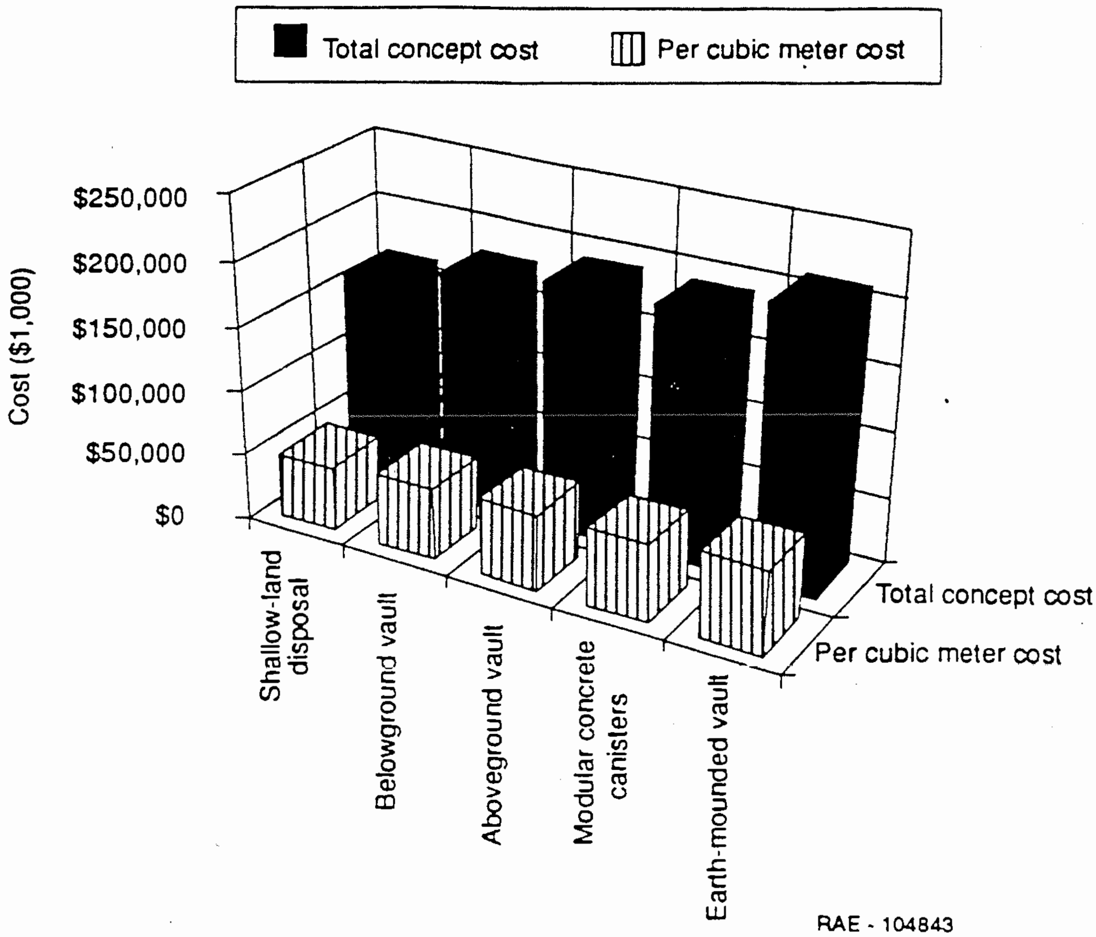


Figure 7-2. Costs for near-surface disposal concepts, all GTCC LLW disposal of.

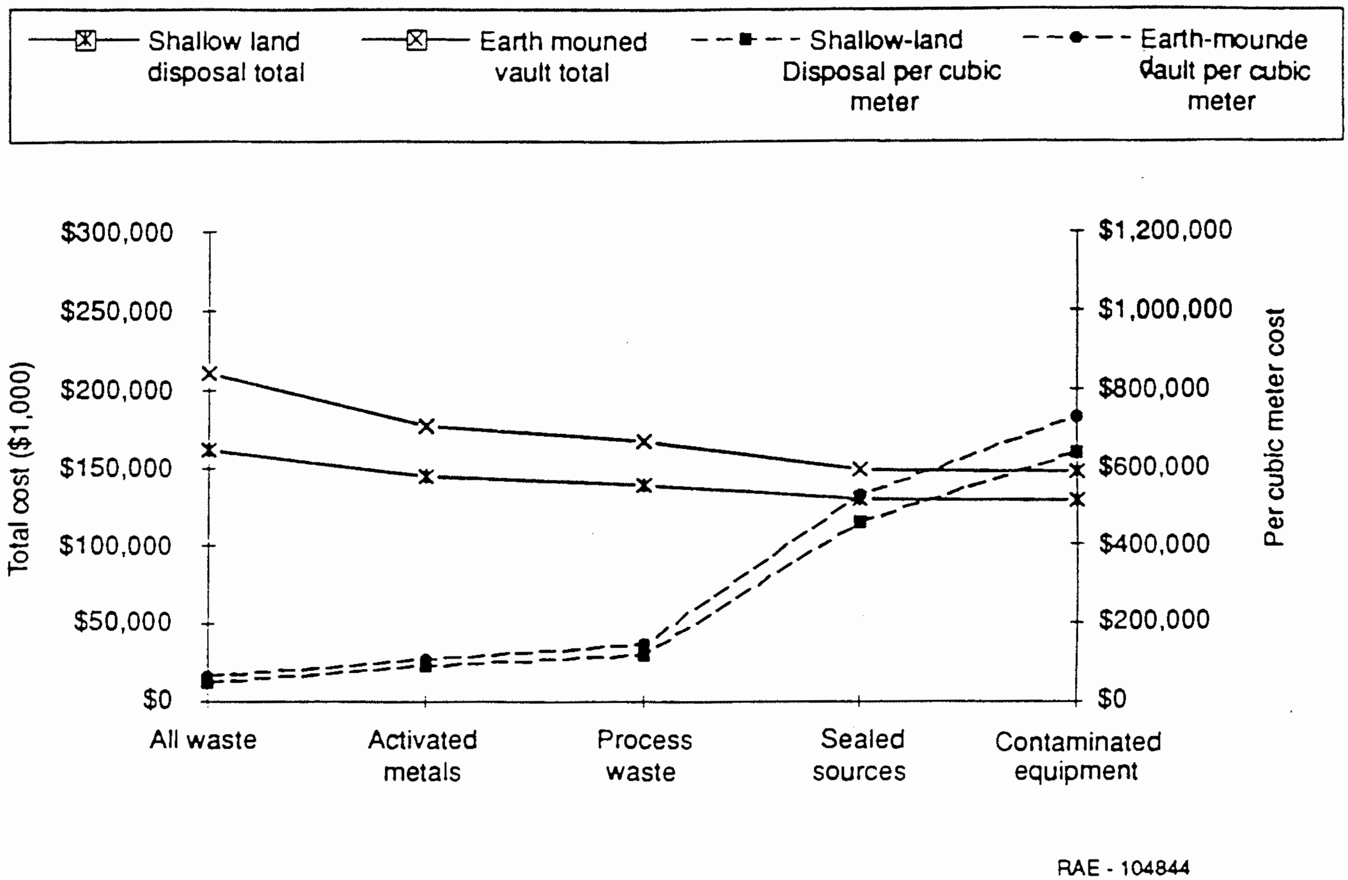


Figure 7-3. Variability of near-surface concept costs by waste type.

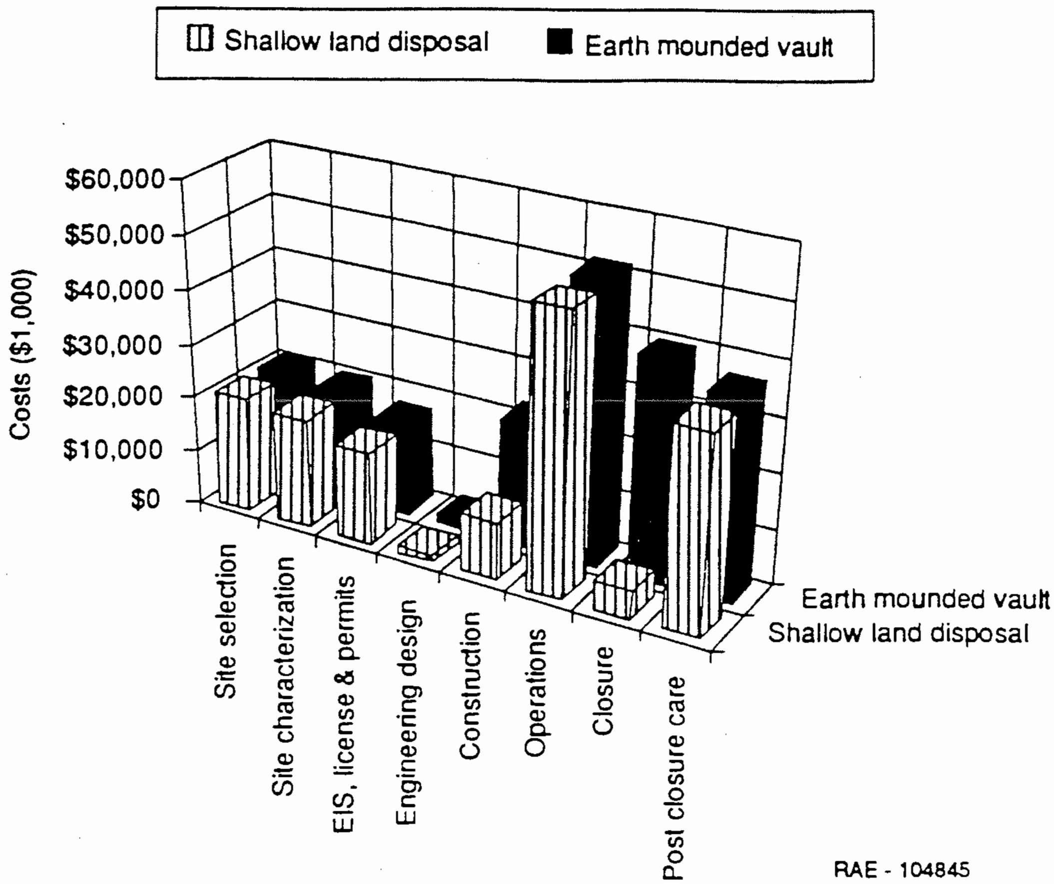


Figure 7-4. Near-surface concept costs by life-cycle phase.

Table 7-4. Range of near-surface shallow-land disposal costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$21,048	$21,048	$21,048	$21,048	$21,048
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$6,192	$6,192	$6,192	$6,192	$6,192
	GW modeling/performance assessment	$1,056	$1,056	$1,056	$1,056	$1,056
2)	Site characterization	$20,172	$20,172	$20,172	$20,172	$20,172
	Site characterization	$14,400	$14,400	$14,400	$14,400	$14,400
	Baseline monitoring	$5,772	$5,772	$5,772	$5,772	$5,772
3)	EIS & licensing & permits	$17,052	$17,052	$17,052	$17,052	$17,052
	Proponent's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$9,180	$9,180	$9,180	$9,180	$9,180
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$1,137	$1,049	$1,024	$978	$973
	Engineering service and design	$1,137	$1,049	$1,024	$978	$973
5)	Construction	$10,775	$8,533	$7,906	$6,714	$6,603
	Construction management	$416	$322	$295	$245	$240
	Construction of support facilities	$5,615	$5,335	$5,256	$5,107	$5,093
	Construction of disposal units	$3,621	$1,810	$1,304	$341	$251
	Building and facility maintenance	$1,123	$1,067	$1,051	$1,021	$1,019
6)	Operations	$51,030	$40,172	$37,134	$31,361	$30,822
	Preoperation payroll	$1,605	$1,605	$1,605	$1,605	$1,605
	Startup of facilities	$268	$268	$268	$268	$268
	Operation payroll	$24,065	$16,845	$14,826	$10,987	$10,629
	Environmental & structural monitoring	$15,099	$13,589	$13,167	$12,364	$12,289
	Regulatory costs	$3,840	$3,840	$3,840	$3,840	$3,840
	Consumables (fuel and utilities)	$2,406	$1,685	$1,483	$1,099	$1,063
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$2,930	$1,758	$1,430	$807	$749
	Equipment maintenance	$586	$352	$286	$161	$150
7)	Closure	$5,212	$3,931	$3,573	$2,892	$2,828
	Disposal site closure & decontamination	$1,649	$1,155	$1,016	$753	$728
	Personnel costs	$1,350	$945	$832	$616	$596
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,507	$1,356	$1,314	$1,234	$1,226
	Fuel, utilities & materials	$135	$94	$83	$62	$60
	Regulatory costs	$96	$96	$96	$96	$96
8)	100 year postclosure care	$36,169	$32,617	$31,624	$29,735	$29,559
	Personnel costs	$6,053	$5,448	$5,278	$4,957	$4,926
	Construction equipment	$900	$810	$785	$737	$733
	Fuel, utilities and materials	$605	$545	$528	$496	$493
	Environmental & structural monitoring	$27,780	$25,002	$24,225	$22,748	$22,610
	Equipment and vehicle maintenance	$180	$162	$157	$147	$147
	Administration costs	$303	$303	$303	$303	$303
	Regulatory costs	$348	$348	$348	$348	$348
	Total:	$162,595	$144,574	$139,533	$129,951	$129,057

Table 7-5. Range of near-surface belowground vault costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$21,048	$21,048	$21,048	$21,048	$21,048
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$6,192	$6,192	$6,192	$6,192	$6,192
	GW modeling/performance assessment	$1,056	$1,056	$1,056	$1,056	$1,056
2)	Site characterization	$20,172	$20,172	$20,172	$20,172	$20,172
	Site characterization	$14,400	$14,400	$14,400	$14,400	$14,400
	Baseline monitoring	$5,772	$5,772	$5,772	$5,772	$5,772
3)	EIS & licensing & permits	$17,052	$17,052	$17,052	$17,052	$17,052
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$9,180	$9,180	$9,180	$9,180	$9,180
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$1,592	$1,290	$1,205	$1,045	$1,030
	Engineering service and design	$1,592	$1,290	$1,205	$1,045	$1,030
5)	Construction	$25,882	$16,226	$13,525	$8,390	$7,912
	Construction management	$1,064	$651	$535	$315	$295
	Construction of support facilities	$5,864	$5,571	$5,489	$5,333	$5,318
	Construction of disposal units	$17,781	$8,891	$6,403	$1,676	$1,235
	Building and facility maintenance	$1,173	$1,114	$1,098	$1,067	$1,064
6)	Operations	$51,414	$40,517	$37,469	$31,675	$31,135
	Preoperation payroll	$1,605	$1,605	$1,605	$1,605	$1,605
	Startup of facilities	$268	$268	$268	$268	$268
	Operation payroll	$24,065	$16,845	$14,826	$10,987	$10,629
	Environmental & structural monitoring	$15,483	$13,935	$13,501	$12,678	$12,601
	Regulatory costs	$3,840	$3,840	$3,840	$3,840	$3,840
	Consumables (fuel and utilities)	$2,406	$1,685	$1,483	$1,099	$1,063
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$2,930	$1,758	$1,430	$807	$749
	Equipment maintenance	$586	$352	$286	$161	$150
7)	Closure	$5,863	$4,402	$3,993	$3,217	$3,144
	Disposal site closure & decontamination	$2,223	$1,556	$1,370	$1,015	$982
	Personnel costs	$1,350	$945	$832	$616	$596
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,584	$1,425	$1,381	$1,297	$1,289
	Fuel, utilities & materials	$135	$94	$83	$62	$60
	Regulatory costs	$96	$96	$96	$96	$96
8)	100 year postclosure care	$36,491	$32,907	$31,904	$29,998	$29,820
	Personnel costs	$6,053	$5,448	$5,278	$4,957	$4,926
	Construction equipment	$900	$810	$785	$737	$733
	Fuel, utilities and materials	$605	$545	$528	$496	$493
	Environmental & structural monitoring	$28,102	$25,291	$24,505	$23,011	$22,872
	Equipment and vehicle maintenance	$180	$162	$157	$147	$147
	Administration costs	$303	$303	$303	$303	$303
	Regulatory costs	$348	$348	$348	$348	$348
	Total:	**$179,513**	**$153,614**	**$146,368**	**$132,597**	**$131,312**

Table 7-6. Range of near-surface aboveground vault costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$21,048	$21,048	$21,048	$21,048	$21,048
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$6,192	$6,192	$6,192	$6,192	$6,192
	GW modeling/performance assessment	$1,056	$1,056	$1,056	$1,056	$1,056
2)	Site characterization	$20,172	$20,172	$20,172	$20,172	$20,172
	Site characterization	$14,400	$14,400	$14,400	$14,400	$14,400
	Baseline monitoring	$5,772	$5,772	$5,772	$5,772	$5,772
3)	EIS & licensing & permits	$17,052	$17,052	$17,052	$17,052	$17,052
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$9,180	$9,180	$9,180	$9,180	$9,180
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$2,081	$1,653	$1,533	$1,305	$1,284
	Engineering service and design	$2,081	$1,653	$1,533	$1,305	$1,284
5)	Construction	$36,504	$22,766	$18,923	$11,618	$10,937
	Construction management	$1,503	$914	$750	$437	$408
	Construction of support facilities	$8,058	$7,655	$7,542	$7,328	$7,308
	Construction of disposal units	$25,332	$12,666	$9,122	$2,387	$1,759
	Building and facility maintenance	$1,612	$1,531	$1,508	$1,466	$1,462
6)	Operations	$51,678	$40,755	$37,699	$31,891	$31,349
	Preoperation payroll	$1,605	$1,605	$1,605	$1,605	$1,605
	Startup of facilities	$268	$268	$268	$268	$268
	Operation payroll	$24,065	$16,845	$14,826	$10,987	$10,629
	Environmental & structural monitoring	$15,747	$14,172	$13,732	$12,894	$12,816
	Regulatory costs	$3,840	$3,840	$3,840	$3,840	$3,840
	Consumables (fuel and utilities)	$2,406	$1,685	$1,483	$1,099	$1,063
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$2,930	$1,758	$1,430	$807	$749
	Equipment maintenance	$586	$352	$286	$161	$150
7)	Closure	$4,879	$3,724	$3,401	$2,787	$2,729
	Disposal site closure & decontamination	$1,187	$831	$731	$542	$524
	Personnel costs	$1,350	$945	$832	$616	$596
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,637	$1,473	$1,427	$1,340	$1,332
	Fuel, utilities & materials	$135	$94	$83	$62	$60
	Regulatory costs	$96	$96	$96	$96	$96
8)	100 year postclosure care	$36,758	$33,147	$32,137	$30,217	$30,038
	Personnel costs	$6,053	$5,448	$5,278	$4,957	$4,926
	Construction equipment	$900	$810	$785	$737	$733
	Fuel, utilities and materials	$605	$545	$528	$496	$493
	Environmental & structural monitoring	$28,369	$25,532	$24,738	$23,230	$23,089
	Equipment and vehicle maintenance	$180	$162	$157	$147	$147
	Administration costs	$303	$303	$303	$303	$303
	Regulatory costs	$348	$348	$348	$348	$348
	Total:	$190,172	$160,317	$151,965	$136,090	$134,609

Table 7-7. Range of near-surface modular concrete canister costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$21,048	$21,048	$21,048	$21,048	$21,048
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$6,192	$6,192	$6,192	$6,192	$6,192
	GW modeling/performance assessment	$1,056	$1,056	$1,056	$1,056	$1,056
2)	Site characterization	$20,172	$20,172	$20,172	$20,172	$20,172
	Site characterization	$14,400	$14,400	$14,400	$14,400	$14,400
	Baseline monitoring	$5,772	$5,772	$5,772	$5,772	$5,772
3)	EIS & licensing & permits	$17,052	$17,052	$17,052	$17,052	$17,052
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$9,180	$9,180	$9,180	$9,180	$9,180
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$1,900	$1,501	$1,389	$1,177	$1,157
	Engineering service and design	$1,900	$1,501	$1,389	$1,177	$1,157
5)	Construction	$33,525	$20,639	$17,034	$10,182	$9,543
	Construction management	$1,384	$832	$678	$384	$357
	Construction of support facilities	$6,919	$6,573	$6,477	$6,293	$6,275
	Construction of disposal units	$23,838	$11,919	$8,584	$2,247	$1,655
	Building and facility maintenance	$1,384	$1,315	$1,295	$1,259	$1,255
6)	Operations	$53,855	$42,056	$38,755	$32,481	$31,895
	Preoperation payroll	$1,605	$1,605	$1,605	$1,605	$1,605
	Startup of facilities	$268	$268	$268	$268	$268
	Operation payroll	$25,781	$18,047	$15,883	$11,770	$11,387
	Environmental & structural monitoring	$15,099	$13,589	$13,167	$12,364	$12,289
	Regulatory costs	$3,840	$3,840	$3,840	$3,840	$3,840
	Consumables (fuel and utilities)	$2,578	$1,805	$1,588	$1,177	$1,139
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$3,712	$2,227	$1,812	$1,022	$949
	Equipment maintenance	$742	$445	$362	$204	$190
7)	Closure	$6,982	$5,170	$4,663	$3,700	$3,610
	Disposal site closure & decontamination	$3,419	$2,393	$2,106	$1,561	$1,510
	Personnel costs	$1,350	$945	$832	$616	$596
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,507	$1,356	$1,314	$1,234	$1,226
	Fuel, utilities & materials	$135	$94	$83	$62	$60
	Regulatory costs	$96	$96	$96	$96	$96
8)	100 year postclosure care	$36,169	$32,617	$31,624	$29,735	$29,559
	Personnel costs	$6,053	$5,448	$5,278	$4,957	$4,926
	Construction equipment	$900	$810	$785	$737	$733
	Fuel, utilities and materials	$605	$545	$528	$496	$493
	Environmental & structural monitoring	$27,780	$25,002	$24,225	$22,748	$22,610
	Equipment and vehicle maintenance	$180	$162	$157	$147	$147
	Administration costs	$303	$303	$303	$303	$303
	Regulatory costs	$348	$348	$348	$348	$348
	Total:	**$190,702**	**$160,255**	**$151,736**	**$135,546**	**$134,035**

Table 7-8. Range of near-surface earth-mounded vault costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$21,048	$21,048	$21,048	$21,048	$21,048
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$6,192	$6,192	$6,192	$6,192	$6,192
	GW modeling/performance assessment	$1,056	$1,056	$1,056	$1,056	$1,056
2)	Site characterization	$20,172	$20,172	$20,172	$20,172	$20,172
	Site characterization	$14,400	$14,400	$14,400	$14,400	$14,400
	Baseline monitoring	$5,772	$5,772	$5,772	$5,772	$5,772
3)	EIS & licensing & permits	$17,052	$17,052	$17,052	$17,052	$17,052
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$9,180	$9,180	$9,180	$9,180	$9,180
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$1,629	$1,387	$1,319	$1,190	$1,178
	Engineering service and design	$1,629	$1,387	$1,319	$1,190	$1,178
5)	Construction	$22,904	$15,551	$13,494	$9,584	$9,220
	Construction management	$923	$610	$522	$355	$340
	Construction of support facilities	$7,317	$6,951	$6,849	$6,654	$6,636
	Construction of disposal units	$13,200	$6,600	$4,754	$1,244	$917
	Building and facility maintenance	$1,463	$1,390	$1,370	$1,331	$1,327
6)	Operations	$51,414	$40,517	$37,469	$31,675	$31,135
	Preoperation payroll	$1,605	$1,605	$1,605	$1,605	$1,605
	Startup of facilities	$268	$268	$268	$268	$268
	Operation payroll	$24,065	$16,845	$14,826	$10,987	$10,629
	Environmental & structural monitoring	$15,483	$13,935	$13,501	$12,678	$12,601
	Regulatory costs	$3,840	$3,840	$3,840	$3,840	$3,840
	Consumables (fuel and utilities)	$2,406	$1,685	$1,483	$1,099	$1,063
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$2,930	$1,758	$1,430	$807	$749
	Equipment maintenance	$586	$352	$286	$161	$150
7)	Closure	$39,972	$28,278	$25,007	$18,789	$18,209
	Disposal site closure & decontamination	$36,332	$25,432	$22,383	$16,587	$16,047
	Personnel costs	$1,350	$945	$832	$616	$596
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,584	$1,425	$1,381	$1,297	$1,289
	Fuel, utilities & materials	$135	$94	$83	$62	$60
	Regulatory costs	$96	$96	$96	$96	$96
8)	100 year postclosure care	$36,491	$32,907	$31,904	$29,998	$29,820
	Personnel costs	$6,053	$5,448	$5,278	$4,957	$4,926
	Construction equipment	$900	$810	$785	$737	$733
	Fuel, utilities and materials	$605	$545	$528	$496	$493
	Environmental & structural monitoring	$28,102	$25,291	$24,505	$23,011	$22,872
	Equipment and vehicle maintenance	$180	$162	$157	$147	$147
	Administration costs	$303	$303	$303	$303	$303
	Regulatory costs	$348	$348	$348	$348	$348
	Total:	$210,680	$176,912	$167,465	$149,508	$147,833

to over $1,000,000. The drilled hole concept has the lowest cost, while the mined cavity has the highest cost. Table 7-9 summarizes and Figure 7-5 shows the spread between the total and per cubic meter costs for intermediate-depth disposal concepts having a capacity to dispose of all GTCC LLW.

If the intermediate-depth concepts are used to dispose of only a portion of the GTCC LLW, costs will vary (see Figure 7-6). The total drilled hole cost decreases from about $273,000,000 to about $201,000,000 , a 26% decrease. The total mined cavity cost decreases by about the same percentage, from $293,000,000 to $219,000,000. Conversely, the per cubic meter costs increase by a factor of more than 10. The drilled hole per-cubic-meter cost increases from about $84,000 to just under $1,000,000, while the same cost for the mined cavity increases from $90,000 to just over $1,000,000.

Figure 7-7 shows total concept costs assigned to the eight phases in the life of the intermediate-depth GTCC LLW concepts. The major difference in cost between the two intermediate-depth concepts is accounted for by the costs for facility construction operations. and closure. Note that the differences in operations and closure costs counter the difference resulting from construction. Smaller differences are found in the costs for design and engineering and postclosure care. The costs for site selection and characterization and licensing, permitting, and environmental documentation are the same for both concepts. The estimated cost for each intermediate-depth concept by phase and cost component are provided in Tables 7-10 and 7-11.

7.3.3 Deep Geologic Disposal Concept Costs

The total order-of-magnitude costs for the two deep geologic GTCC LLW disposal concepts range from $285,000,000 to $396,000,000. The corresponding per cubic meter costs range from $118,000 to over $1,500,000. As in the case of the intermediate-depth concepts, the drilled hole concept has the lowest cost, while the mined cavity has the highest cost. Table 7-12 summarizes and Figure 7-8 shows the spread between the total and per-cubic-meter costs for deep geologic disposal concepts having the capacity to dispose of all GTCC LLW.

Should the deep geologic concepts be used to dispose of only a portion of the GTCC LLW, costs will vary as shown in Figure 7-9. The total drilled hole cost decreases from $383,000,000 to $285,000,000, a 26% decrease. The total mined cavity cost decreases by about 23%, from $396,000,000 to $307,000,000. As with the other disposal concepts, the per-cubic-meter costs increase by a factor of

Table 7-9. Intermediate-depth disposal concept costs for disposal of all GTCC LLW.

Disposal Concept	Total Life Cycle Cost	Per Cubic Meter Cost
Drilled holes	$273,143,000	$84,000
Mined cavity	$292,593,000	$90,000

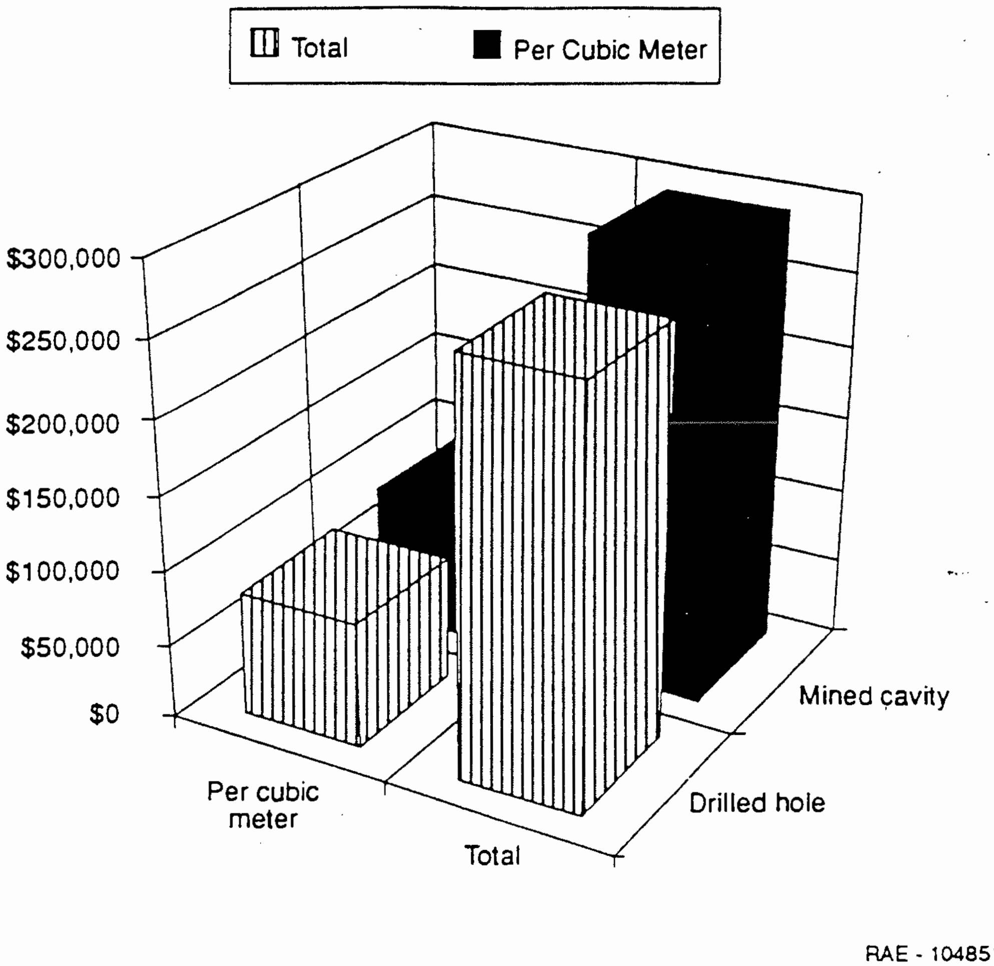


Figure 7-5. Costs for intermediate-depth concepts, all GTCC LLW disposed of.

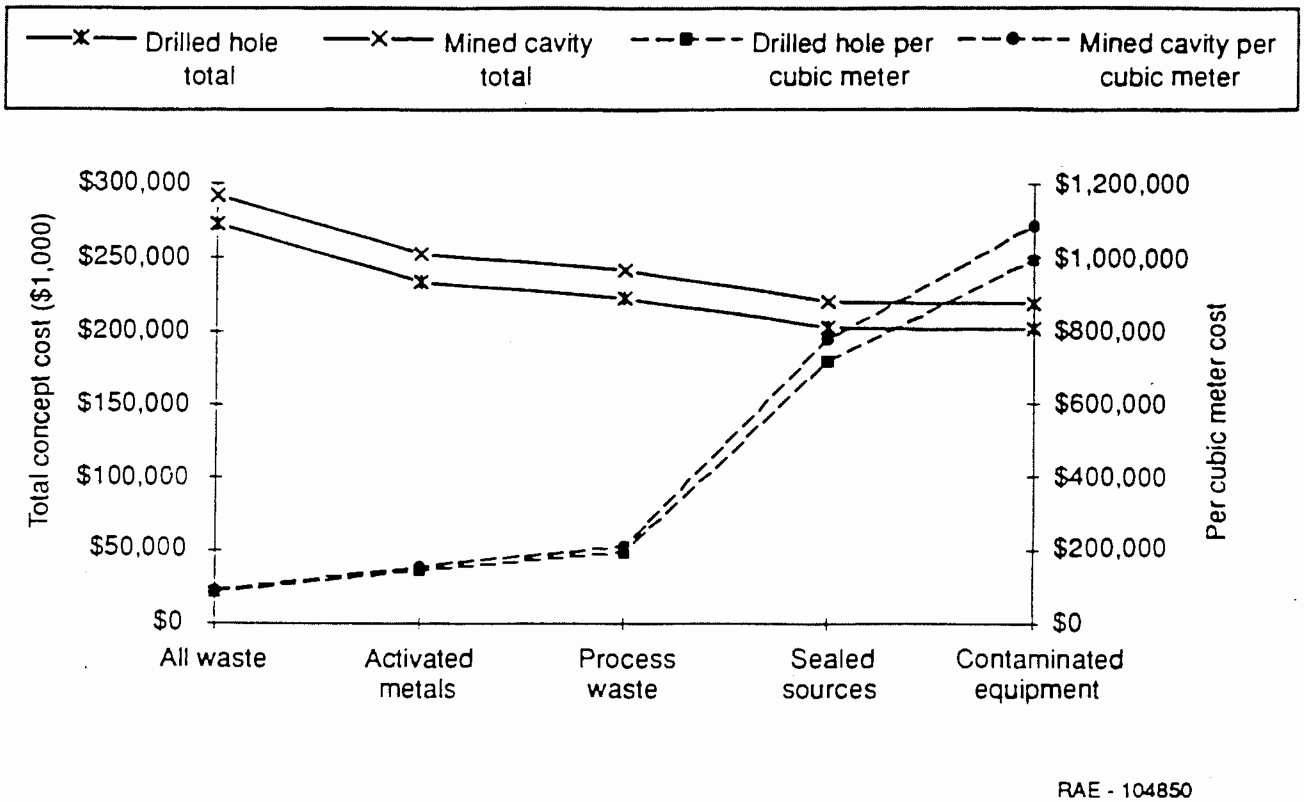


Figure 7-6. Variability of intermediate-depth concept costs by waste type.

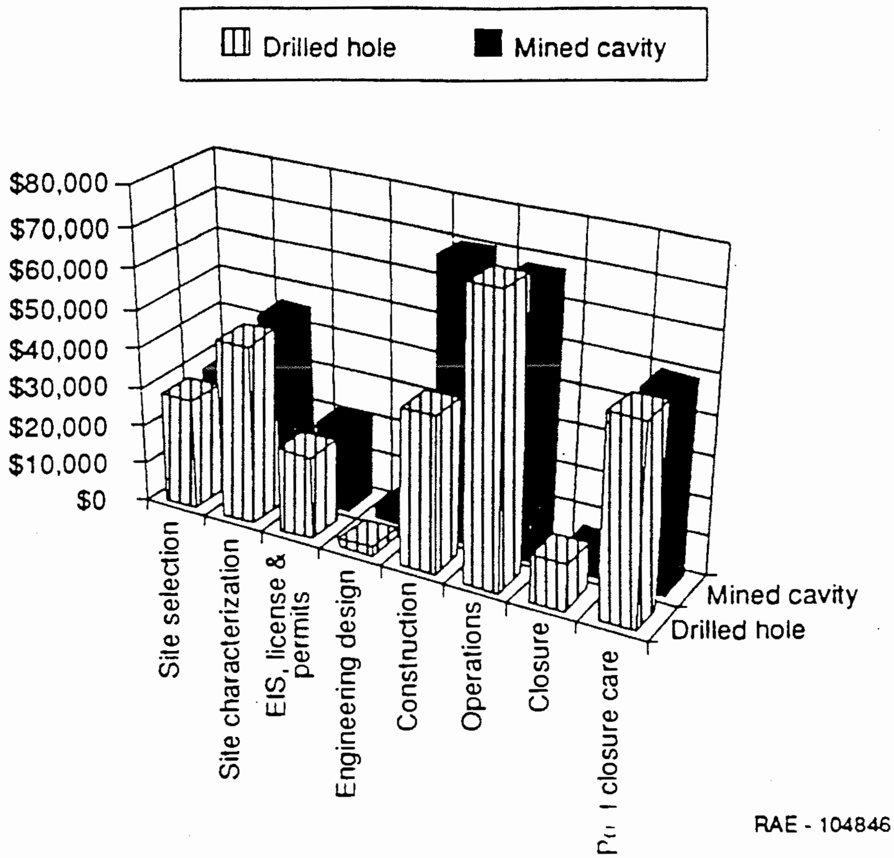


Figure 7-7. Intermediate-depth concept costs by life-cycle phase.

Table 7-10. Range of intermediate-depth drilled hole costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$28,272	$28,272	$28,272	$28,272	$28,272
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$12,888	$12,888	$12,888	$12,888	$12,888
	GW modeling/performance assessment	$1,584	$1,584	$1,584	$1,584	$1,584
2)	Site characterization	$45,831	$45,831	$45,831	$45,831	$45,831
	Site characterization	$36,000	$36,000	$36,000	$36,000	$36,000
	Baseline monitoring	$9,831	$9,831	$9,831	$9,831	$9,831
3)	EIS & licensing & permits	$21,372	$21,372	$21,372	$21,372	$21,372
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$13,500	$13,500	$13,500	$13,500	$13,500
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$2,435	$1,957	$1,824	$1,570	$1,546
	Engineering service and design	$2,435	$1,957	$1,824	$1,570	$1,546
5)	Construction	$39,673	$24,179	$19,844	$11,605	$10,837
	Construction management	$1,642	$978	$792	$439	$406
	Construction of support facilities	$7,751	$7,363	$7,255	$7,049	$7,030
	Construction of disposal units	$28,730	$14,365	$10,346	$2,708	$1,995
	Building and facility maintenance	$1,550	$1,473	$1,451	$1,410	$1,406
6)	Operations	$72,877	$58,217	$54,196	$46,553	$45,840
	Preoperation payroll	$1,724	$1,724	$1,724	$1,724	$1,724
	Startup of facilities	$703	$703	$703	$703	$703
	Operation payroll	$28,109	$19,676	$17,317	$12,833	$12,415
	Environmental & structural monitoring	$27,347	$24,612	$23,847	$22,393	$22,257
	Regulatory costs	$5,760	$5,760	$5,760	$5,760	$5,760
	Consumables (fuel and utilities)	$3,099	$1,968	$1,732	$1,283	$1,241
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$4,921	$2,953	$2,402	$1,355	$1,258
	Equipment maintenance	$984	$591	$480	$271	$252
7)	Closure	$12,093	$9,000	$8,134	$6,490	$6,336
	Disposal site closure & decontamination	$7,032	$4,922	$4,332	$3,210	$3,106
	Personnel costs	$1,588	$1,111	$978	$725	$701
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$2,695	$2,426	$2,350	$2,207	$2,194
	Fuel, utilities & materials	$159	$111	$98	$72	$70
	Regulatory costs	$144	$144	$144	$144	$144
8)	100 year postclosure care	$50,591	$45,616	$44,224	$41,578	$41,331
	Personnel costs	$6,337	$5,703	$5,526	$5,189	$5,157
	Construction equipment	$495	$446	$432	$406	$403
	Fuel, utilities and materials	$634	$570	$553	$519	$516
	Environmental & structural monitoring	$42,187	$37,968	$36,788	$34,545	$34,336
	Equipment and vehicle maintenance	$99	$89	$86	$81	$81
	Administration costs	$317	$317	$317	$317	$317
	Regulatory costs	$522	$522	$522	$522	$522
	Total:	**$273,143**	**$234,443**	**$223,696**	**$203,271**	**$201,365**

Table 7-11. Range of intermediate-depth mined cavity costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$28,272	$28,272	$28,272	$28,272	$28,272
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$12,888	$12,888	$12,888	$12,888	$12,888
	GW modeling/performance assessment	$1,584	$1,584	$1,584	$1,584	$1,584
2)	Site characterization	$45,831	$45,831	$45,831	$45,831	$45,831
	Site characterization	$36,000	$36,000	$36,000	$36,000	$36,000
	Baseline monitoring	$9,831	$9,831	$9,831	$9,831	$9,831
3)	EIS & licensing & permits	$21,372	$21,372	$21,372	$21,372	$21,372
	Proponent's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$13,500	$13,500	$13,500	$13,500	$13,500
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$3,506	$2,948	$2,792	$2,496	$2,468
	Engineering service and design	$3,506	$2,948	$2,792	$2,496	$2,468
5)	Construction	$70,298	$52,332	$47,306	$37,753	$36,862
	Construction management	$2,941	$2,171	$1,956	$1,547	$1,509
	Construction of support facilities	$10,036	$9,534	$9,394	$9,127	$9,102
	Construction of disposal units	$55,314	$38,720	$34,077	$25,253	$24,430
	Building and facility maintenance	$2,007	$1,907	$1,879	$1,825	$1,820
6)	Operations	$67,760	$52,897	$48,820	$41,069	$40,346
	Preoperation payroll	$1,724	$1,724	$1,724	$1,724	$1,724
	Startup of facilities	$762	$762	$762	$762	$762
	Operation payroll	$30,485	$21,339	$18,781	$13,918	$13,464
	Environmental & structural monitoring	$18,899	$17,009	$16,480	$15,476	$15,382
	Regulatory costs	$5,760	$5,760	$5,760	$5,760	$5,760
	Consumables (fuel and utilities)	$3,336	$2,134	$1,878	$1,392	$1,346
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$5,470	$3,282	$2,670	$1,506	$1,398
	Equipment maintenance	$1,094	$656	$534	$301	$280
7)	Closure	$6,146	$4,668	$4,254	$3,46[illegible]	$3,395
	Disposal site closure & decontamination	$1,930	$1,351	$1,189	$88[illegible]	$852
	Personnel costs	$1,588	$1,111	$978	$725	$701
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,[illegible]	$1,666	$1,614	$1,515	$1,506
	Fuel, utilities & materials	[illegible]	$111	$98	$72	$70
	Regulatory costs	$144	$144	$144	$144	$144
8)	100 year postclosure care	$49,408	$44,551	$43,192	$40,609	$40,368
	Personnel costs	$6,337	$5,703	$5,526	$5,189	$5,157
	Construction equipment	$495	$446	$432	$406	$403
	Fuel, utilities and materials	$634	$570	$553	$519	$516
	Environmental & structural monitoring	$41,004	$36,904	$35,756	$33,576	$33,37[illegible]
	Equipment and vehicle maintenance	$99	$89	$86	$81	$81
	Administration costs	$317	$317	$317	$317	$317
	Regulatory costs	$522	$522	$522	$522	$522
	Total:	**$292,593**	**$252,871**	**$241,839**	**$220,870**	**$218,914**

Table 7-12. Deep geologic disposal concept costs for disposal of all GTCC LLW.

Disposal Concept	Total Life Cycle Cost	Per Cubic Meter Cost
Drilled holes	$383,385,000	$118,000
Mined cavity	$396,186,000	$122,000

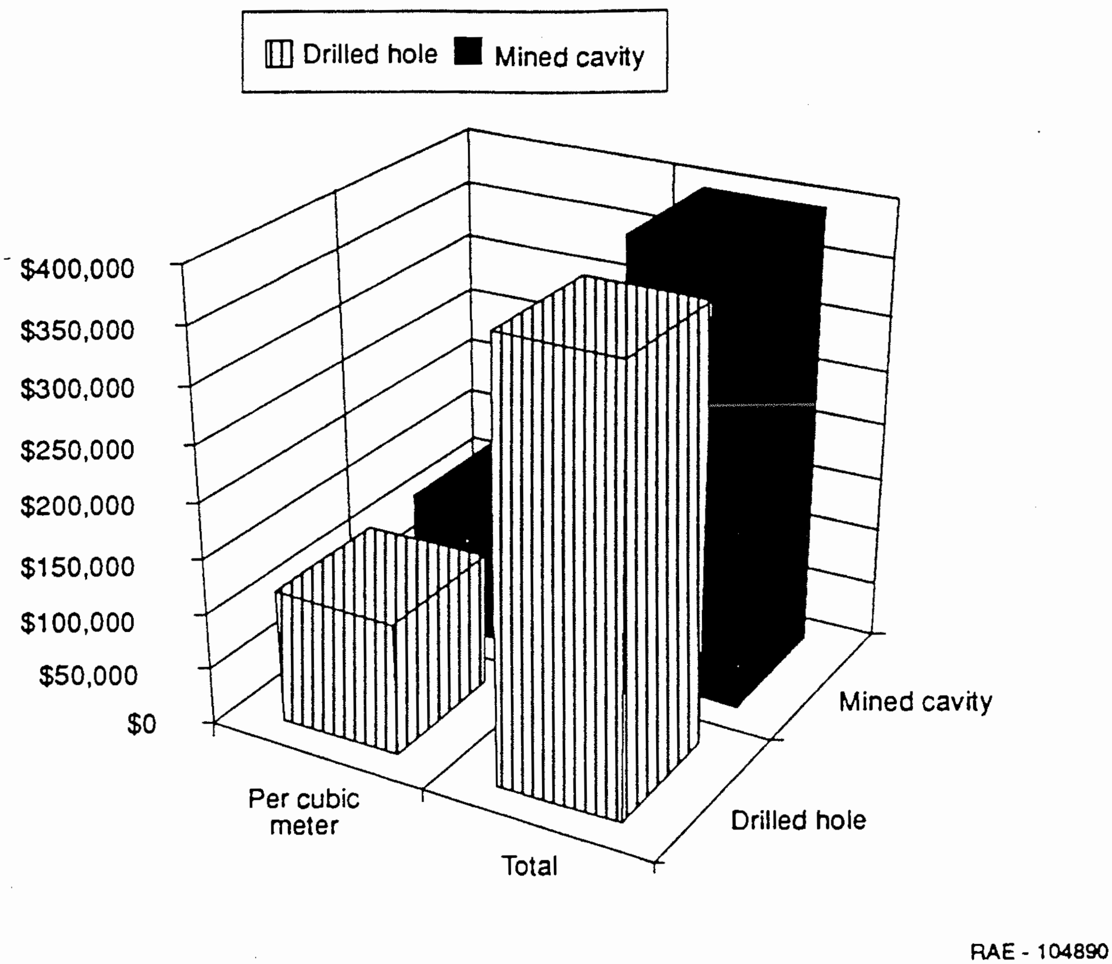


Figure 7-8. Costs for deep geologic concepts, all GTCC LLW disposed of.

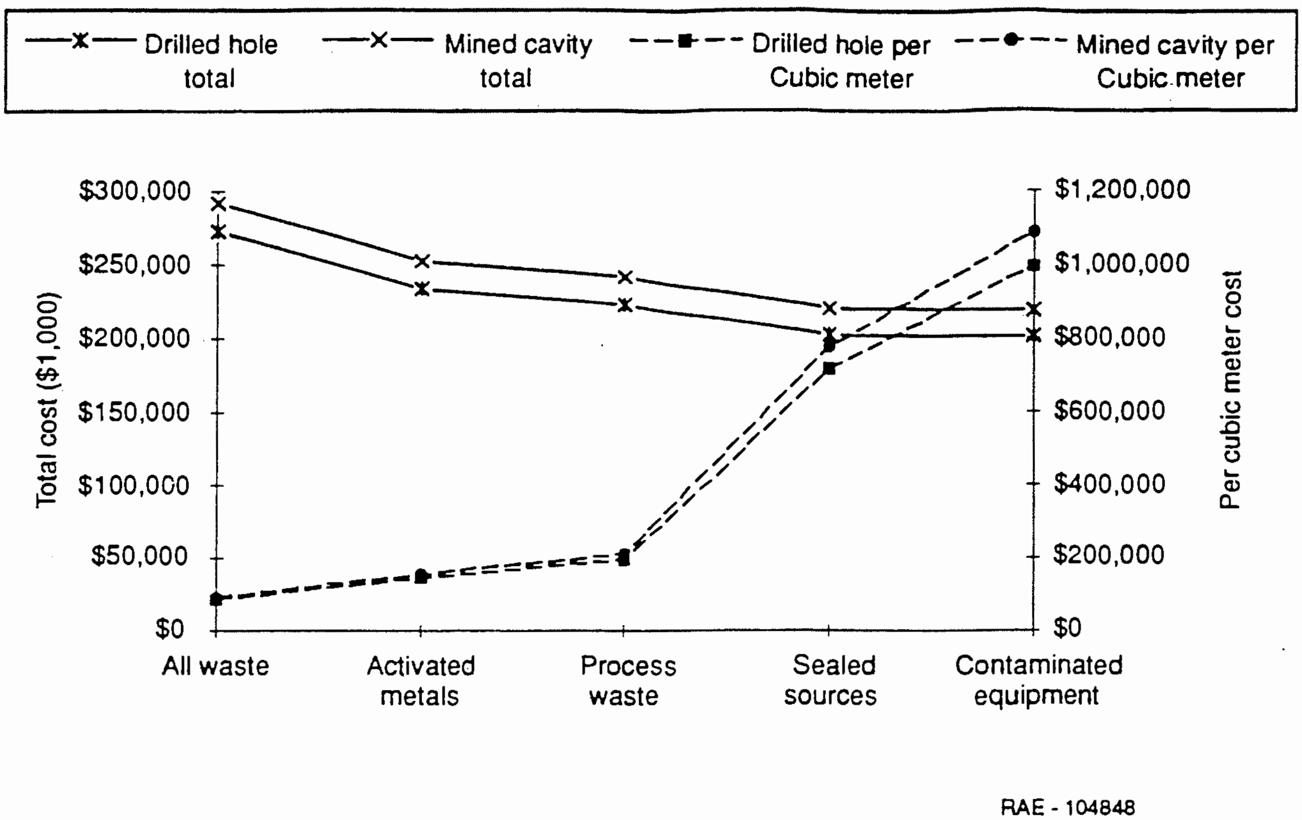


Figure 7-9. Variability of deep geologic concept costs by waste type.

more than 10. The drilled hole per-cubic-meter cost increases from about $118,000 to over $1,400,000, while the same cost for the mined cavity increases from $122,000 to over $1,500,000.

Figure 7-10 shows total concept costs assigned to the eight phases in the life of the deep geologic GTCC LLW concepts. The relationships between the cost per life cycle phase are the same as those for the intermediate-depth concepts. The majority of the difference in cost between the two deep geologic concepts is accounted for by the costs for facility construction, operations, and closure. Note that the differences in operations and closure costs counter the difference resulting from construction. Smaller differences are found in the costs for design and engineering and postclosure care. The costs for site selection and characterization, licensing, permitting, and environmental documentation are the same for both concepts. The estimated cost for each deep geologic concept by phase and cost component are provided in Tables 7-13 and 7-14.

7.4 Recommended Disposal Systems Order-Of-Magnitude Costs

The technical evaluation of the 13 potential GTCC LLW disposal concepts identified disposal systems as being the most technically feasible. These disposal systems are made up of disposal concepts listed in Table 7-15.

Individual disposal concept costs developed in Section 7.3 help determine the order-of-magnitude costs for each recommended disposal system. The costs listed in Tables 7-4 through 7-8, 7-10, 7-11, 7-13, and 7-14 for each appropriate disposal concept were used to arrive at the order-of-magnitude costs for the recommended disposal systems.

It is assumed that the recommended arid site disposal system makes use of one of the three recommended concepts. Order-of-magnitude costs for a near-surface modular concrete canister facility sized to dispose of all GTCC LLW are reported in Table 7-7. Similar cost data for the intermediate-depth drilled holes and mined cavities are reported in Tables 7-10 and 7-11, respectively. The total cost and per-cubic-meter costs for an arid site disposal system would range from $190,702,000 and $59,000/m^3 to $292,593,000 and $90,000/m^3, as shown in Table 7-16.

It is assumed that the recommended humid site disposal system makes use of one of the four recommended disposal concepts. The use of combinations of concepts is not assumed. Order-of-magnitude costs for the intermediate-depth drilled holes and mined cavities and for the deep geologic

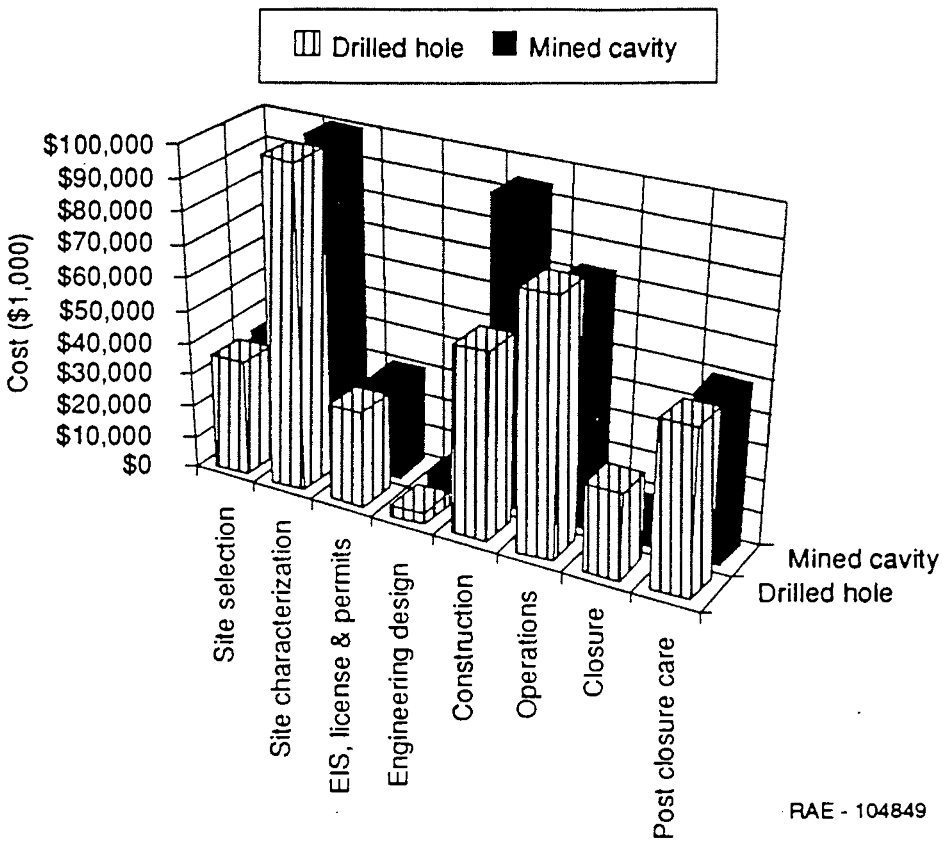


Figure 7-10. Deep geologic concept costs by life cycle phase.

Table 7-13. Range of deep geologic drilled hole costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$36,024	$36,024	$36,024	$36,024	$36,024
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$19,584	$19,584	$19,584	$19,584	$19,584
	GW modeling/performance assessment	$2,640	$2,640	$2,640	$2,640	$2,640
2)	Site characterization	$99,831	$99,831	$99,831	$99,831	$99,831
	Site characterization	$90,000	$90,000	$90,000	$90,000	$90,000
	Baseline monitoring	$9,831	$9,831	$9,831	$9,831	$9,831
3)	EIS & licensing & permits	$30,012	$30,012	$30,012	$30,012	$30,012
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$22,140	$22,140	$22,140	$22,140	$22,140
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$3,576	$2,837	$2,630	$2,237	$2,200
	Engineering service and design	$3,576	$2,837	$2,630	$2,237	$2,200
5)	Construction	$57,924	$33,304	$26,417	$13,325	$12,104
	Construction management	$2,428	$1,371	$1,075	$513	$461
	Construction of support facilities	$7,751	$7,363	$7,255	$7,049	$7,030
	Construction of disposal units	$46,195	$23,098	$16,636	$4,354	$3,208
	Building and facility maintenance	$1,550	$1,473	$1,451	$1,410	$1,406
6)	Operations	$78,639	$63,211	$59,056	$51,158	$50,422
	Preoperation payroll	$1,724	$1,724	$1,724	$1,724	$1,724
	Startup of facilities	$739	$739	$739	$739	$739
	Operation payroll	$29,561	$20,693	$18,212	$13,496	$13,056
	Environmental & structural monitoring	$27,347	$24,612	$23,847	$22,393	$22,257
	Regulatory costs	$9,600	$9,600	$9,600	$9,600	$9,600
	Consumables (fuel and utilities)	$3,532	$2,069	$1,821	$1,350	$1,306
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$4,921	$2,953	$2,402	$1,355	$1,258
	Equipment maintenance	$984	$591	$480	$271	$252
7)	Closure	$26,440	$19,072	$17,010	$13,092	$12,727
	Disposal site closure & decontamination	$21,283	$14,898	$13,112	$9,717	$9,400
	Personnel costs	$1,588	$1,111	$978	$725	$701
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$2,695	$2,426	$2,350	$2,207	$2,194
	Fuel, utilities & materials	$159	$111	$98	$72	$70
	Regulatory costs	$240	$240	$240	$240	$240
8)	100 year postclosure care	$50,939	$45,964	$44,572	$41,926	$41,679
	Personnel costs	$6,337	$5,703	$5,526	$5,189	$5,157
	Construction equipment	$495	$446	$432	$406	$403
	Fuel, utilities and materials	$634	$570	$553	$519	$516
	Environmental & structural monitoring	$42,187	$37,968	$36,788	$34,545	$34,336
	Equipment and vehicle maintenance	$99	$89	$86	$81	$81
	Administration costs	$317	$317	$317	$317	$317
	Regulatory costs	$870	$870	$870	$870	$870
	Total:	$383,385	$330,254	$315,552	$287,606	$284,999

Table 7-14. Range of deep geologic mined cavity costs ($1,000).

		All waste	Activated metals	Process waste	Sealed sources	Contaminated solids
1)	Site selection	$36,024	$36,024	$36,024	$36,024	$36,024
	Site screening	$13,800	$13,800	$13,800	$13,800	$13,800
	Site precharacterization	$19,584	$19,584	$19,584	$19,584	$19,584
	GW modeling/performance assessment	$2,640	$2,640	$2,640	$2,640	$2,640
2)	Site characterization	$99,831	$99,831	$99,831	$99,831	$99,831
	Site characterization	$90,000	$90,000	$90,000	$90,000	$90,000
	Baseline monitoring	$9,831	$9,831	$9,831	$9,831	$9,831
3)	EIS & licensing & permits	$30,012	$30,012	$30,012	$30,012	$30,012
	Proponant's environmental assessment & license application	$5,100	$5,100	$5,100	$5,100	$5,100
	Licensing	$22,140	$22,140	$22,140	$22,140	$22,140
	Permits.	$2,772	$2,772	$2,772	$2,772	$2,772
4)	Engineering design	$4,816	$4,051	$3,836	$3,429	$3,391
	Engineering service and design	$4,816	$4,051	$3,836	$3,429	$3,391
5)	Construction	$94,411	$69,211	$62,162	$48,762	$47,512
	Construction management	$3,979	$2,898	$2,596	$2,021	$1,968
	Construction of support facilities	$10,036	$9,534	$9,394	$9,127	$9,102
	Construction of disposal units	$78,389	$54,872	$48,293	$35,788	$34,622
	Building and facility maintenance	$2,007	$1,907	$1,879	$1,825	$1,820
6)	Operations	$72,958	$57,493	$53,327	$45,410	$44,672
	Preoperation payroll	$1,724	$1,724	$1,724	$1,724	$1,724
	Startup of facilities	$786	$786	$786	$786	$786
	Operation payroll	$31,435	$22,005	$19,366	$14,352	$13,884
	Environmental & structural monitoring	$18,899	$17,009	$16,480	$15,476	$15,382
	Regulatory costs	$9,600	$9,600	$9,600	$9,600	$9,600
	Consumables (fuel and utilities)	$3,720	$2,200	$1,937	$1,435	$1,388
	Office equipment	$230	$230	$230	$230	$230
	Construction/operation equipment	$5,470	$3,282	$2,670	$1,506	$1,398
	Equipment maintenance	$1,094	$656	$534	$301	$280
7)	Closure	$8,378	$6,259	$5,667	$4,540	$4,435
	Disposal site closure & decontamination	$4,066	$2,846	$2,505	$1,856	$1,796
	Personnel costs	$1,588	$1,111	$978	$725	$701
	Construction equipment	$475	$285	$232	$131	$121
	Environmental & structural monitoring	$1,851	$1,666	$1,614	$1,515	$1,506
	Fuel, utilities & materials	$159	$111	$98	$72	$70
	Regulatory costs	$240	$240	$240	$240	$240
8)	100 year postclosure care	$49,756	$44,899	$43,540	$40,957	$40,716
	Personnel costs	$6,337	$5,703	$5,526	$5,189	$5,157
	Construction equipment	$495	$446	$432	$406	$403
	Fuel, utilities and materials	$634	$570	$553	$519	$516
	Environmental & structural monitoring	$41,004	$36,904	$35,756	$33,576	$33,373
	Equipment and vehicle maintenance	$99	$89	$86	$81	$81
	Administration costs	$317	$317	$317	$317	$317
	Regulatory costs	$870	$870	$870	$870	$870
	Total:	**$396,186**	**$347,780**	**$334,399**	**$308,965**	**$306,593**

Table 7-15. Component concepts for the recommended waste disposal systems.

Arid site disposal system
Near-surface modular concrete canister, or
Intermediate-depth drilled holes, or
Intermediate-depth mined cavity.
Humid site disposal system
Intermediate-depth mined cavity, or drilled hole, or
Deep geologic mined cavity, or drilled hole.

Table 7-16. Range of costs for recommended arid site disposal system.

Recommended concepts	Total order-of-magnitude cost	Per-cubic-meter cost
Near-surface modular concrete canisters	$190,702,000	$59,000
Intermediate-depth drilled holes	$273,143,000	$84,000
Intermediate-depth mined cavity	$292,593,000	$90,000

drilled holes and mined cavities are reported in Tables 7-10, 7-11, 7-13, and 7-14 respectively. The total cost and per-cubic-meter costs for a humid site disposal system range from \$273,143,000 and \$84,000/m^3 to \$396,186,000 and \$122,000/m^3, as shown in Table 7-17.

Table 7-17. Range of costs for recommended humid site disposal system.

Recommended concepts	Total order-of-magnitude cost	Per-cubic-meter cost
Intermediate-depth drilled hole	$273,143,000	$84,000
Intermediate-depth mined cavity	$292,593,000	$90,000
Deep geologic drilled hole	$383,385,000	$118,000
Deep geologic mined cavity	$396,186,000	$122,000

8. CONCLUSIONS

Section 3 described the methodology used to evaluate the confinement and intrusion performance of five near-surface, four intermediate-depth, and four deep geologic GTCC LLW disposal concepts. Section 4 defined the characteristics of the GTCC LLW, disposed concepts and their components, and of arid and humid hypothetical disposal sites. The detailed performance of each disposal concept for disposal of each of four categories of GTCC LLW and for disposal of all GTCC LLW was reported in Section 5. In Section 6 the technically feasible GTCC LLW disposal systems were identified. Order-of-magnitude costs for each of the individual disposal concepts and for the technically feasible GTCC LLW disposal systems were developed in Section 7. Section 8 reports the conclusions concerning the technical feasibility of GTCC LLW disposal and the potential costs of such disposal that can be made based on the analyses conducted.

8.1 Conclusions on Technical Feasibility of GTCC LLW Disposal

The analysis to determine the relative performance of the 13 GTCC LLW disposal concepts required development of significant amounts of data on the long-term performance of engineered structures and the disposal sites. While this data are technically sound, they are at best estimates with large uncertainties associated with each. While these uncertainties make the absolute values calculated for each performance measure questionable, it is believed that the relationships between disposal concepts, waste categories, and sites will remain generally the same as the uncertainties are reduced. The following are the technical conclusions that are expected to remain unchanged as GTCC LLW disposal concepts are developed.

- Overall concept performance, when all GTCC LLW is considered, is dominated by the performance characteristics for sealed sources

- The same disposal concept at an arid site performs better than when used at a humid site

- Barrier lifetimes on the order of 200 to 3,000 years have negligible effect on the overall releases and doses from the disposal concepts

- The rate of release of radionuclides from activated metals is controlled by the corrosion rate of the metal components

- Greater distance from or travel time to the exposure point (the one meter well in this analysis) has the greatest effect on groundwater concentrations and radiation doses

- The radionuclides released from the GTCC LLW and reaching the groundwater and thereby resulting in the radiation dose all have half lives on the order of several thousand years or more. Some like C-14, I-129, and Tc-99 are also very mobile in the environment. The successful GTCC LLW disposal system must focus on containment of these radionuclides and reducing the potential be exposed to them.

8.2 Conclusions on Potential Cost of GTCC LLW Disposal Systems

The order-of-magnitude costs developed in this analysis are realistic given the level of site an design data available and the assumptions that were used. As with the performance measure results, the order-of-magnitude estimates will change as the disposal concepts are refined. It is expected, however, that the relationship between the estimates for each disposal concept will generally stay the same as each concept is refined. The following are the economic conclusions that are expected to remain unchanged as GTCC LLW disposal concepts are developed.

- If placed in a dedicated stand-alone facility, the per-cubic-meter disposal cost for GTCC LLW will be on the order of $50,000 to $100,000

- The economics of GTCC LLW disposal will not support the use of different disposal concepts and sites (assuming each is a standing along facility) for different categories of GTCC LLW.

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