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Alternative Methods for Disposal of Low-Level Radioactive Wastes

Task 2a: Technical Requirements for Belowground Vault Disposal of Low-Level Radioactive Waste

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Current practice in the US for disposal of commercial low-level radioactive wastes (LLW) is burial in shallow trenches. In 1983, approximately 110,000 cubic meters of these wastes were disposed of at the three operating commercial sites. Three additional sites have ceased operations in the past decade and are awaiting technical and institutional determinations that will allow for final closure. Although shallow land burial in trenches may continue to be practiced, it is likely that techniques for engineered disposal will be introduced to the NRC or states for licensing consideration within the next few years.

The belowground vault disposal alternative is one of several methods that may be proposed. In this report, the term belowground vault disposal refers to a near-surface disposal alternative in which the wastes would be disposed of in vaults constructed belowground in excavations and covered with soil. The vaults would be comprised of engineered roof and walls. The floor would be natural soil or rock, treated soil or rock, or engineered materials. Access would be through openings in the roof or walls.

The experience and knowledge gained with this method are described and updated in this report. Extrapolation of this short-term experience indicates that the belowground vault disposal method is capable of satisfying the performance objectives specified by the NRC in 10 CFR Part 61 Subpart C.

A generic description of the features and components and operation of a belowground vault disposal facility is provided. Features and components that could enhance the long-term performance are also described.

The existing criteria developed for near-surface disposal (10 CFR Part 61 Subpart D) were assessed for applicability to the belowground vault disposal method in Task 1 of this study and were reassessed in Task 2, as reported herein. With few exceptions, these criteria were found to be applicable in the reassessment. These conclusions differ slightly from the Task 1 findings, as explained herein.

Additional technical considerations that should be addressed are recommended. These considerations include:

a. The need for assessment of the occurrence and potential adverse impacts from dispersive soils, corrosive soils, solution cavities, liquefiable soils, expansive soils and areas undergoing land subsidence.

b. The need to plan for individual disposal unit closure.

c. The need for submittal of a detailed plan for remedial actions should they become necessary. This plan should identify specific events that would trigger specific actions and the reaction times involved.

Finally, research is recommended for unresolved questions about the long-term durability and performance of materials used in engineered facilities.

Appendix A, which describes factors that impair the long-term durability of concrete and discusses design and construction methods that can be used to minimize the adverse impacts, is a step in this direction.

CONTENTS

LIST OF FIGURES

ACKNOWLEDGEMENTS

This report presents the results of subtask 2b of the US Nuclear Regulatory Commission (NRC) - sponsored study, "Criteria for Evaluating Engineered Facilities," performed by personnel of the US Army Engineer Waterways Experiment Station (WES) Geotechnical Laboratory under interagency agreement no. NRC-02-83-046 dated 31 May 1983.

Mr. James Shaffner was the NRC technical monitor. His advice and support are greatly appreciated. Mr. David Bennett was principal investigator and coauthor of this report, with Mr. James B. Warriner. Mr. Robert H. Denson, Structures Laboratory, prepared Appendix A. The patience and diligence of Mrs. Mary Anne Kirklin in typing this report and the drafting work by Mr. Bennie Washington are gratefully acknowledged.

The work was performed under the general supervision of Mr. J. S. Huie, Chief, Rock Mechanics Application Group (RMAG), Engineering Geology and Rock Mechanics Division (EGRMD), Geotechnical Laboratory (GL) and Dr. Don C. Banks, Chief, EGRMD.

Dr. William F. Marcuson III was Chief of the Getoechnical Laboratory during this study.

Mr. Fred Brown and Dr. Robert W. Whalin were Technical Directors of WES. COL Robert C. Lee was Commander and Director and COL Allen F. Grum was Director of WES during this study.

1. INTRODUCTION

1.1 Background

The Atomic Energy Act of 1954 and the Energy Reorganization Act of 1974 gave the US Nuclear Regulatory Commission (NRC) the responsibility for assuring and maintaining public health and safety, as may be affected by commercial nuclear facilities, including facilities for the disposal of low level adioactive waste (LLW).

The National Low Level Radioactive Waste Policy Act of 1980 (Public Law 96-573) gave the individual states responsibility for the management and safe disposal of all commercial LLW generated within their borders. The act allows, subject to congressional approval, that each state may enter into regional compacts with neighboring states to establish and operate regional disposal sites.

The NRC has established uniform procedures for licensing and regulating the land disposal of LLW. The procedures are set forth in the Code of Federal Regulations 10 CFR Part 61. Subpart D of 10 CFR Part 61 and related regulatory guidance provide specific technical criteria for land disposal. Specific sections of Subpart D provide technical criteria related to siting, design, operations and closure of a near-surface disposal facility. Subsections were reserved for methods other than near-surface disposal.

Current practice in the US is to dispose of commercial LLW by burial in shallow trenches. In 1983 approximately 110,000 cubic meters of these wastes were disposed of at the three commercially operated disposal facilities. Waste disposal at three additional sites has ceased in the past decade and these sites are awaiting permanent closure.

Although shallow land burial in trenches may continue to be practiced, it is likely that other techniques for engineered disposal may be submitted to the NRC or the states for licensing consideration within the next few years. It is important that the NRC establish uniform criteria, or guidance, by which engineered facilities may be evaluated and that such criteria or guidance be compatible with the performance objectives set forth in 10 CFR Part 61 Subpart C.

1.2 Purpose and Scope

The overall purpose of this study was to ensure that the technical criteria or guidance required to completely evaluate 5 alternative methods of LLW disposal were available. The methods considered in this study were aboveground vaults, belowground vaults, earth mounded concrete bunkers, mined cavities, and shafts. Criteria or guidance related to site suitability, design, operations, closure, and monitoring as listed in 10 CFR Part 61, paragraphs 61.50 through 61.53, were to be assessed. Where judged to be appropriate, recommendations were to be made to modify existing criteria and to address additional technical issues.

Guidance related to the implementation of criteria for acceptable waste forms and classes that would be appropriate for disposal in specific engineered facilities are also important areas of consideration. However, development of guidance for acceptable waste forms or waste classifications was beyond the scope of this study.

Development of conceptual designs was also not within the scope of this study. However, important features of the various alternatives were illustrated and discussed as they pertain to the satisfaction of the performance objectives. Although segregation of wastes prior to disposal in engineered facilities may be desirable for economic or political reasons, segregation has not been assumed as a requirement for this study.

Cost estimates were not prepared or reported for any of these alternative methods. It is recognized that guidance on conceptual designs and acceptable waste forms and classes appropriate for disposal using these alternatives would be useful to the states or individuals considering them, and that detailed costs would be an important consideration in their adoption. However, the most important issues are whether these methods can meet the performance objectives of Subpart C and how their performance can be judged.

The study was divided into 3 main tasks. Previous work was described in the Task 1 report (Bennett and others, 1984), and included descriptions of all 5 alternatives, summaries of the experience with each method, and an initial assessment of the applicability of existing technical criteria relating to site suitability, design, operations, closure, and monitoring.

This report, one of a series, contains the results of subtask 2b of the investigation. Separate reports were prepared for each method investigated. The reports pertaining to the aboveground vault, belowground vault, earth mounded concrete bunkers, and shaft disposal methods were each issued as one of a series of 4. Although each of these methods has some contrasts with shallow land burial, they are similar to existing near surface disposal methods.

The mined cavity disposal alternative is quite different from near surface disposal. Consequently, during the course of the study, the NRC decided to deal with this method separately from the others.

1.3 Organization

Each of the Task 2 reports has been organized in parallel format as described below.

Each report shares a common introductory section. In Part 2, the performance objectives are listed, the experience with the disposal alternative is summarized and updated, the unit operations and features and components of the particular alternative disposal facility are described, and the performance capabilities are summarized.

The technical criteria recommendations are developed in Part 3. The criteria are reassessed one by one, drawing from the assessment and conclusions made in the Task 1 report. The organizational scheme used is to list each criterion as it appears in 10 CFR Part 61, and discuss its objective and relevance to belowground vault disposal. Next a recommendation is made to:

a. Retain the criterion as is,

b. Not apply the criterion in the evaluation of the particular alternative, or

c. Modify the criterion to make it applicable to the particular alternative.

Any departures or changes from the position taken in the Task 1 report are noted and explained. This procedure is followed for each criterion.

At the end of each Criteria section, i.e. site suitability, design, etc., suggested additional technical considerations that should be addressed are discussed. These considerations (which are implied from 10 CFR 61.12) may form the basis for additional criteria, if judged to be necessary by the NRC. Specific supplemental criteria are not given in prescriptive language. Rather, the issues that should be addressed and the reasoning behind them are stated. This method of presentation is thought to be more appropriate than offering specific criteria, as it allows the NRC to consider those issues and develop specific wording that it considers appropriate on a point by point basis. Alternatively, the NRC may wish to provide guidance without changes or additions to existing criteria.

In Part 4, conclusions and recommendations are offered on the feasibility of the disposal concept, the modified criteria and supplemental considerations, and on unresolved issues and research required to resolve them.

All references are listed after the body of the report. A glossary of major terms follows the references.

Because concrete is likely to play an important role in engineered disposal facilities, factors that impair long term durability of concrete and design and construction practices that can be used to minimize adverse impacts are discussed in Appendix A.

2. THE BELOWGROUND VAULT DISPOSAL ALTERNATIVE

In the following paragraphs, the alternative is described, including design considerations for major components or features of the method, the experience gained with its use is summarized and updated from the Task 1 report, and performance capabilities are discussed. Features or components that could enhance the method's performance are also discussed.

The discussion at the end of this section of performance capabilities of the disposal alternative is directed toward satisfaction of the performance objectives listed in 10 CFR Part 61 Subpart C, paragraphs 61.40 through 61.44.

It should be noted that for any method to be considered by the NRC for licensing for disposal of low-level radioactive wastes, it must be capable of satisfying the performance objectives, which are quoted below.

2.1 Performance Objectives

Paragraph 61.40 - "General requirement. Land disposal facilities must be sited, designed, operated, closed, and controlled after closure so that reasonable assurance exists that exposures to humans are within the limits established in the performance objectives in paragraphs 61.41 through 61.44."

Paragraph 61.41 - "Protection of the general population from releases of radioactivity. Concentrations of radioactive material which may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable."

Paragraph 61.42 - "Protection of individuals from inadvertent intrusion. Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contactng the waste at any time after active institutional controls over the disposal site are removed."

Paragraph 61.43 - "Protection of individuals during operations. Operations at the land disposal facility must be conducted in compliance with the standards for radiation protection set out in Part 20 of this chapter" (10 CFR Part 20) "except for releases of radioactivity in effluents from the land disposal facility, which shall be governed by paragraph 61.41 of this part. Every reasonable effort shall be made to maintain radiation exposures as low as is reasonably achievable."

Paragraph 61.44 - "Stability of the disposal site after closure. The disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site and to eliminate to the extent practicable the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care are required."

2.2 Experience with the Method

In the following paragraphs, the experience with storage or disposal of radioactive wastes in belowground vaults is summarized.

As used in this report, the term 'belowground vault alternative' refers to any enclosed engineered structure constructed below the surface of the earth by cut and cover construction or built aboveground and then covered with earth. Although vaults can be built inside underground openings, this option is not considered in this report. This option is more appropriately considered within the mined cavity alternative.

2.2.1 Storage of TRU Wastes at Oak Ridge National Laboratory (ORNL).

Oak Ridge National Laboratory uses belowground vaults in its Solid Waste Storage Area No. 5. The facility is termed the 'TRU' structure and is currently used for retrievable storage of transuranic radioactive waste materials. Figure 1 is an aerial photograph of Area No. 5, showing the belowground vault in the middle foreground. The structure was not designed or built with expectation of use for long-term LLW disposal but the design does incorporate a number of features in common with the concept of a LLW belowground disposal vault.

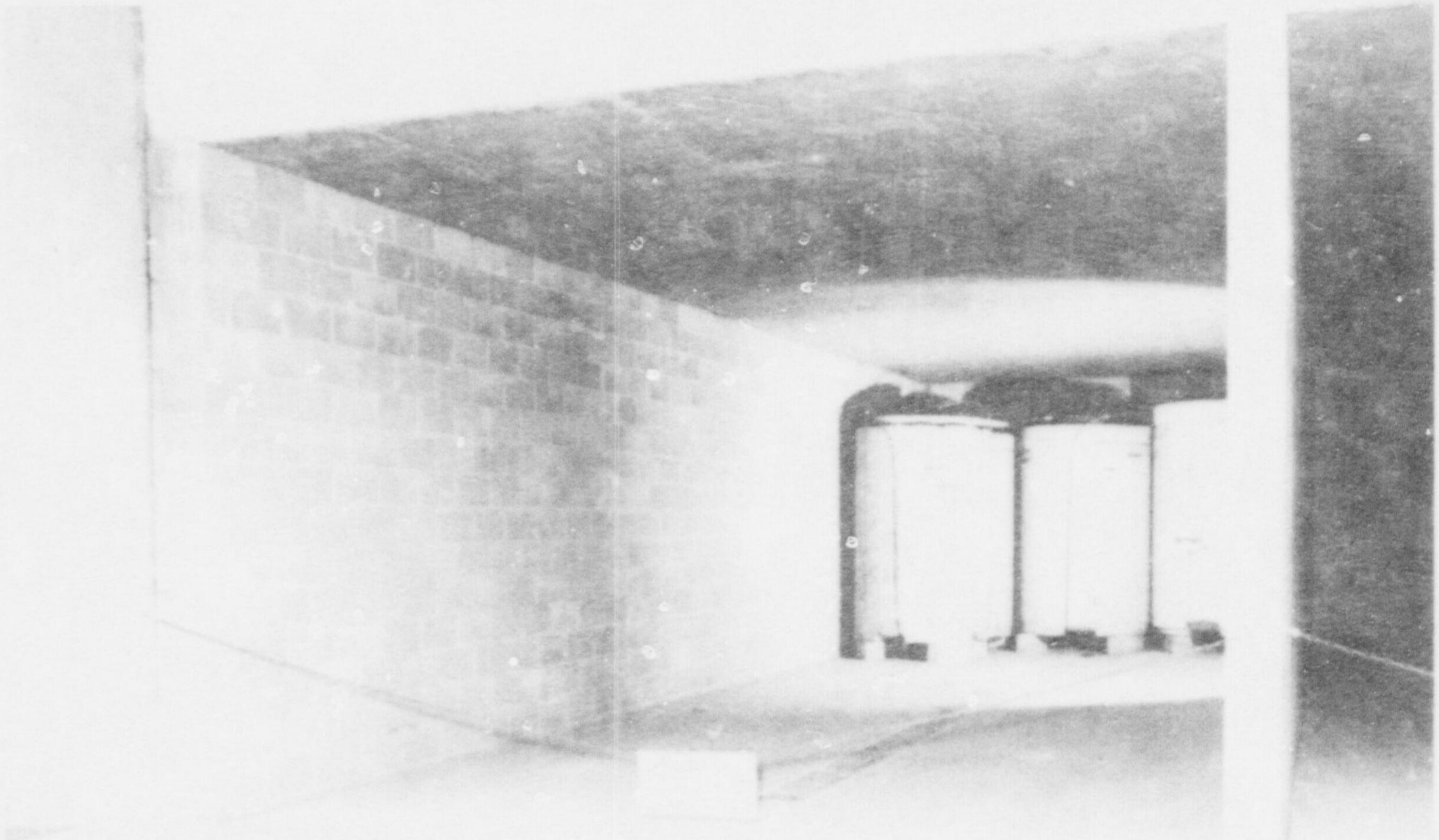
The structure is constructed with three walls, a floor, and a roof fabricated from reinforced cast-in-place concrete. Earth was placed as fill above the completed structure. Figure 2 shows waste-bearing concrete casks inside one of the bays. The bays are separated by masonry walls in this structure. Water drainage is achieved with a grate-covered floor channel in each bay and a perimeter drain system outside the vault. The floor drain carries any contaminated water to a monitored collection sump and has possible application to long-term disposal vault design. The exterior drain was not intended for monitoring but is a requirement for stability of the underground structure. The perimeter exterior drain system does not discharge in a controlled manner but is amenable to collection and monitoring procedures. Closure of each bay is accomplished by constructing a masonry wall incorporating two air vents and a man-access hole. Figure 3 is a closer view of the vault structure showing a completed closed bay and an adjacent open bay. A detail of the vault design not indicated in the figures is the existence of two access holes about 2 in. in diameter in the ceiling. These holes allow air venting, interior air sampling, and access by viewing devices after closure. With appropriate appurtenances for security and filtering, access holes like these could be incorporated in an acceptable long-term disposal vault.

2.2.2 LLW Storage at Chalk River Nuclear Laboratory, Ontario, Canada, and at Whiteshell Nuclear Research Establishment, Manitoba, Canada

Variations of shallow belowground vaults have also been used for LLW storage in Ontario, Canada, at the Chalk River Nuclear Laboratory (CRNL) and at

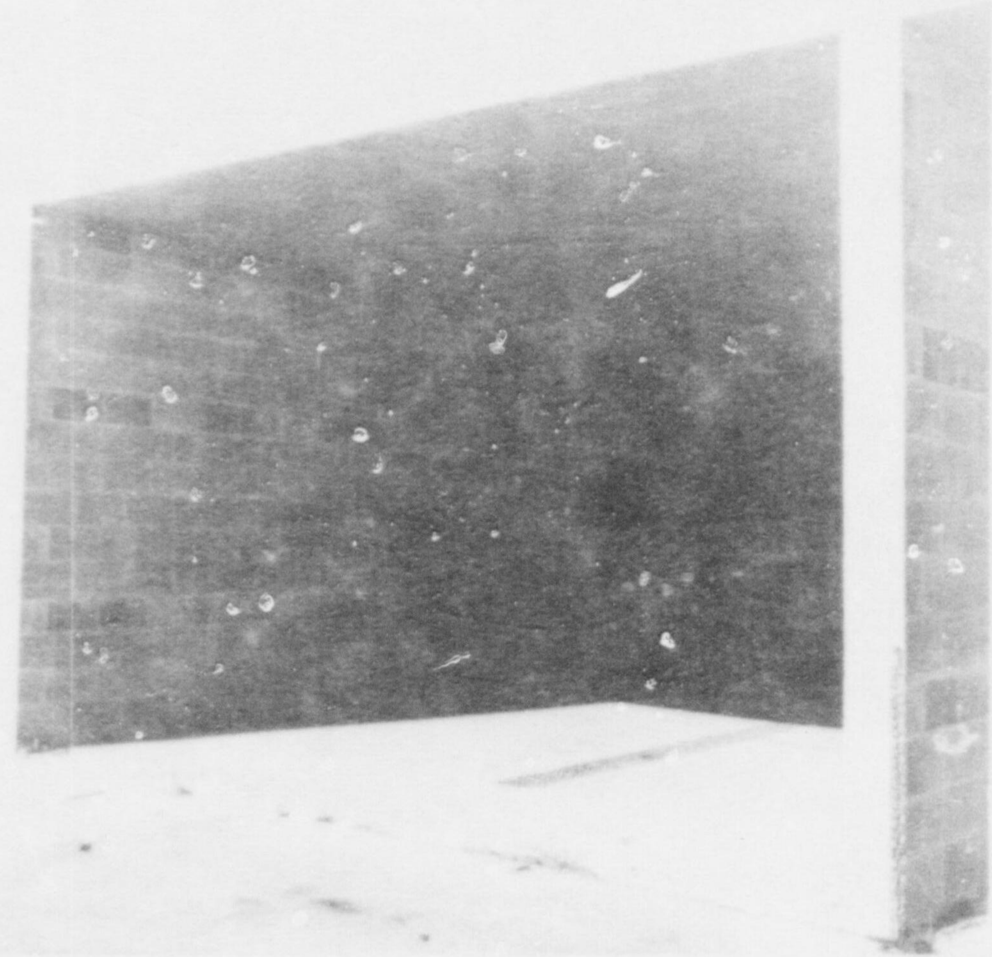
The belowground vault shown in the middle foreground is currently used for retrievable storage of transuranic radioactive waste. The structure was constructed from reinforced cast-in-place concrete and has earth placed as fill above the completed structure. Individual bays within the vault are separated by masonry walls.

Figure 1. Belowground Vault at Oak Ridge National Laboratory, Solid Waste Storage Area No. 5. Source: Photograph courtesy of Oak Ridge National Laboratory



The concrete casks shown within the bay contain transuranic radioactive wastes. the bays within the vault are separated by masonry walls. The grate-covered floor drain within each bay carries any drainage water to a collection sump for monitoring. Not visible in the photo are two 3-in.-diam access holes in the ceiling for monitoring purposes.

Figure 2. Waste-bearing concrete casks within a Belowground Vault, Oak Ridge National Laboratory, Solid Waste Storage Area No. 5. Source: Photograph courtesy of Oak Ridge National Laboratory



The chained area shown is a bay of a belowground vault which has been temporarily closed (same bay as shown in Figure 2.) The closure shown is by means of a masonry wall incorporating two air vents and a man-access hole. This closure method is not recommended for long-term LLW disposal, but may be acceptable for temporary closure during disposal operations in an adjacent bay.

Figure 3. Temporary closure of a bay within a Belowground Vault, Oak Ridge National Laboratory, Solid Waste Storage Area No. 5. Source: Photograph courtesy of Oak Ridge National Laboratory.

Whiteshell Nuclear Research Establishment (WNRE) in Manitoba, Canada (Ferady, 1982 and 1983; Charlesworth and Carter, 1982; and Morrison, 1974). The structures at each of these sites have evolved over the years from rectangular bunker type concrete trenches (61 m x 4.9 m x 2.4 m deep) to the currently used cylindrical concrete designs (6 m diam x 4 to 5 m deep) with removable weather-proof caps. Major wastes stored in these facilities include ion exchange resins and filters, Cobalt-60 sources, and irradiated piping.

2.3 Operations, Design Considerations, and Features of a Belowground Vault Disposal Facility

A disposal facility for LLW that uses belowground vaults as the disposal units could have a layout and plan of operations similar in some respects to existing shallow land burial facilities. Some operations, design considerations, and features would be unique requirements for this method. Similarly, some operations and features should be considered absolute requirements, while others may be desirable but not essential under all conditions.

2.3.1 Unit Operations

The primary unit operations required at a belowground vault disposal facility are listed below:

a. Trucks loaded with wastes will be checked in at the entrance, the cargo and manifest checked, and appropriate instructions given to the driver.

b. The truck will proceed to the secure operations area, i.e., the actual disposal area, or to a temporary storage area, from which the waste packages would be transferred for disposal later.

c. The waste packages will be unloaded using a mobile crane and placed in the disposal units using a mobile crane or forklift, depending on configuration of the vault access. Control of human occupation time within the vault interiors is recommended, commensurate with waste activity levels and shielding and venting provisions. One possible method to reduce exposures is to use remote waste handling and emplacement through openings in the roof.

d. After being unloaded, the truck will be surveyed for contamination and decontaminated, if necessary, before leaving the site.

e. Vaults may be temporarily closed after each shipment is placed. Temporary closure should prevent rainwater or runoff from entering the vault.

f. As the vaults reach capacity, they should be closed. If the vault design includes drains, then closure procedures must account for these drains although continued monitoring of these drains may be advantageous. Waste emplacement access openings must be closed.

g. Sampling and monitoring stations, including surface and subsurface points, must be establishd and maintained. Characterization of the subsurface and material properties should continue through the design and construction phase and modifications should be made as necessary to design features to complement site characteristics and enhance performance.

h. Laboratory tests and analyses will be required periodically to verify satisfactory performance and establish a data base from which trends and anomalies may be discerned.

i. Personnel training and public relations work will be required.

j. Clearing and grading of new disposal areas and establishment and maintenance of surface water management features will be required.

k. Additional disposal units must be constructed periodically, including necessary appurtenances.

l. Surveying is required to establish new disposal-area boundaries and disposal unit locations.

m. Record keeping is required for waste receipts, disposal locations, unusual incidents, personnel records including worker exposures, quality control test results, sampling and monitoring data, and permits and licenses.

2.3.2 Features and Components and Design Considerations

Design considerations for the primary features and components of a below-ground vault disposal facility are listed and discussed below:

a. The actual disposal site includes the land for disposal areas, disposal units, buffer zones, and auxiliary operations. These components are discussed separately below. Specific unit configurations, such as size, orientation, and spacing are not specified, but considerations for architectural or construction components such as the excavation, floor, walls, and covers are presented.

b. Security fences, guard shacks, and a truck check-in station are required for control of access and egress.

c. An operations building is required, from which all disposal operations would be initiated.

d. An administration building is required and should include facilities for office work, records storage and retrieval, visitor waiting-room facilities, convenience facilities, and storage areas. Ample parking areas should be provided. The administration building should be outside the secure operations area to minimize the number of employees and visitors that must be checked in and out.

e. Access roads are needed for transportation of wastes from entrance to disposal units and for maintenance and monitoring. To assure that roads on the site do not interfere with site closure and stabilization plans, they should be designed so that construction equipment and other anticipated vehicles will not damage monitoring stations or completed disposal areas during normal operational activities. Roads should be of sufficient width and durability that vehicles may be safely operated on the roads without damaging nearby disposal units which are operating or have been closed. Road surfaces should be designed to prevent concentrated infiltration or runoff which would interfere with other design objectives, i.e., minimizing infiltration, providing a stable site surface and establishing a vegetative cover.

f. A repair shop should be provided and should include tools and facilities for maintenance and repair of operating equipment and fabrication, modification, or repair of special devices, equipment, or sampling and testing equipment.

g. An overpack-container fabrication and storage area may or may not be necessary or desirable, depending on the plan of operations and customer needs.

h. A testing laboratory should be provided and should include necessary testing equipment and computer facilities for storage, retrieval, plotting, and analysis of test and monitoring data. It is considered important to have these facilities onsite to avoid delays between sampling and testing. In this way, the site manager and his staff can quickly detect any abnormalities or trends that might develop and take action as needed to correct them.

i. A truck decontamination facility is recommended. The waste water must be properly treated and disposed of.

j. Personnel and clothing decontamination facilities should be available.

k. An equipment storage building should be provided.

l. A temporary waste storage area should be available, including unloading facilities, for use in case of temporary shutdown of disposal operations due to inclement weather or during periods of peak waste receipts. This storage area should be designed to minimize contact of rainfall and runoff water with waste packages.

m. Operating equipment must be available, including some or all of the following:

(1) Pickups and vans for transporting personnel and visitors.

(2) Trucks and trailers for transporting waste packages, construction materials, and heavy equipment.

(3) Front end loader/backhoe excavator to excavate foundations and drainage channels and place backfill and drainage material.

(4) Elevating scrapers for excavation of disposal units and placement of earth covers over vaults.

(5) Forklift for use in temporary storage operations and for disposal operations if access to vaults or storage areas is through openings in walls (Figures 2 and 4).

(6) Drill rig(s) for exploration boreholes, piezometers, and wells.

(7) Mobile crane for unloading wastes, and placing waste packages in disposal vaults if access is through openings in roof.

The sizes, number required, and even the need for some of the above equipment would be dependent on the operating plan, site conditions, and customer needs.

n. A nominal inventory of spare parts and tools for repairs to vital or emergency equipment is recommended.

o. Survey markers and survey equipment are required.

p. Surface water management features should include components for collection, transport and discharge, as necessary to prevent flooding, ponding, and erosion. Pangburn and Pennifill (1982) have discussed the goals of surface water management and provided guidance for achieving these goals.

Accepted practice for management of surface water at commercial shallow land burial sites has been discussed by Tucker (1983), along with recommendations for improved performance. Tucker discussed methods to maximize surface runoff and to minimize infiltration through the cover. Some of these recommendations are already being practiced at commercial and DOE disposal sites, and others will probably be adopted as new sites are opened. These recommendations relate to surface and trench bottom grading practices, proper trench orientation in relation to surface contours, and progressive and sequential trench construction. Establishment of a vegetative cover is also recommended. Differences in conditions and design requirements are noted for arid regions.

Additional measures could be implemented to improve surface drainage and cover performance. Most of these measures would add to the operating expenses, but would reduce long-term maintenance. For example, rock-filled or paved drainage ditches would reduce erosion and maintenance problems. Guidelines are given in Tucker (1983) report for evaluating the erosion potential of various unlined drainage ditch profiles and various soil types.

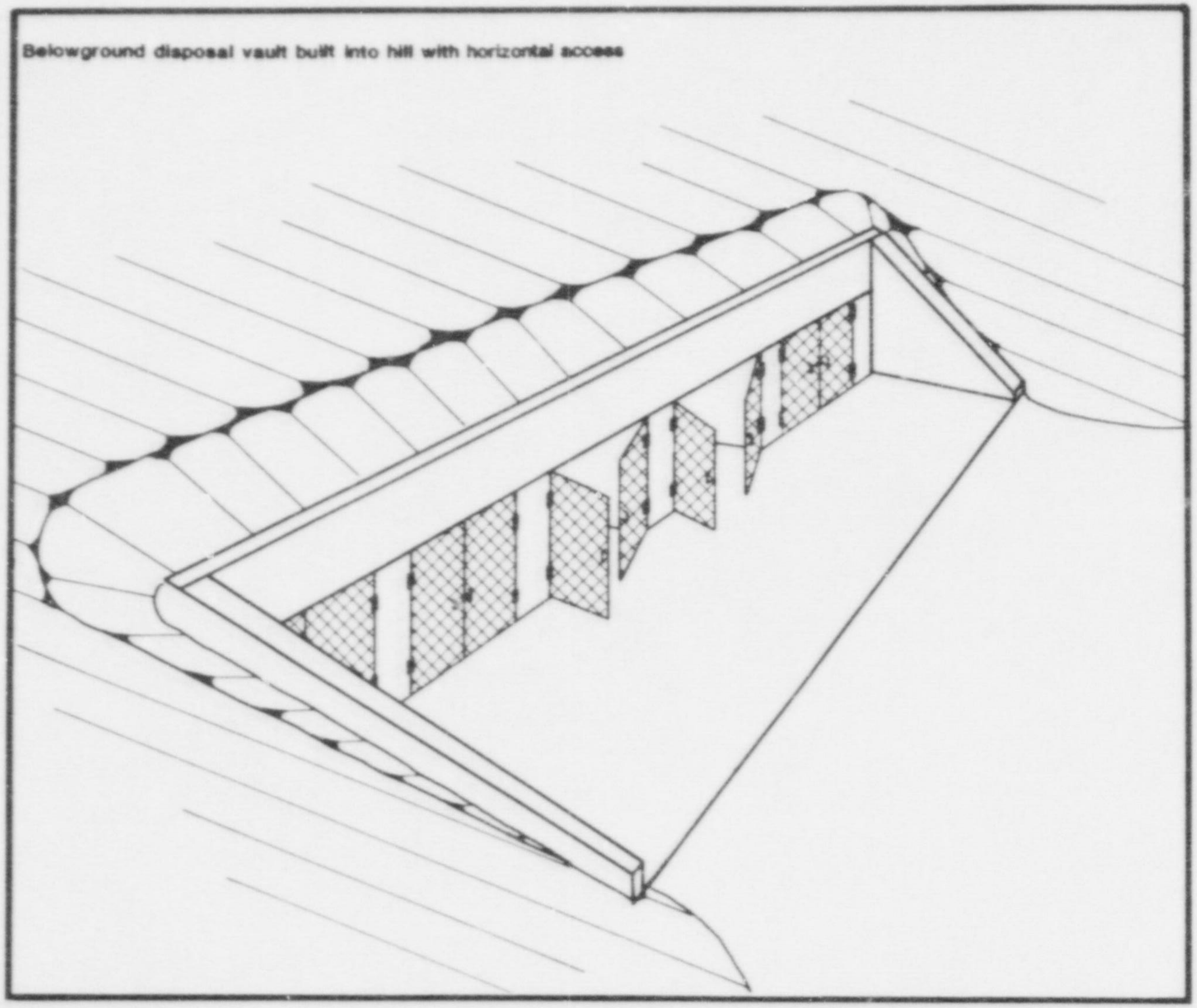


Figure 4. Compartmentalized belowground LLW disposal vault units constructed inside of hill with access through door openings in walls.

q. Quality control testing equipment should be sufficient to verify performance of engineering materials and structures. It should include apparatus to sample and test site cast concrete, backfill moisture and density, and waste package integrity.

r. Monitoring devices should include piezometers, wells, water sampling devices, air sampling stations, and weather stations.

Sedlett and others (1982) have developed a handbook for environmental monitoring of LLW disposal sites.

Lutton and others (1982a, 1982b, and 1983), in a series of three reports, described the parameters of concern for monitoring a shallow land burial site, test methods, and equipment required to measure and monitor these parameters, and suggested frequency of measurements.

In addition to environmental monitoring, structural performance and long-term durability of materials used in vault construction should be monitored. The monitoring program must extend from the preoperational site investigation program, through the operating period, and for some time after closure. Therefore, the instruments used should be rugged and reliable over extended periods of time. Monitoring locations should be chosen that allow for periodic repair or replacement of monitoring devices as necessary.

s. Disposal unit components. The components of a belowground vault are discussed below in chronological order of construction. Figures 5a-f illustrate the sequence of "cut and cover" construction, from excavation, to vault construction, through placement of the final cover for this concept. Variations are, of course, possible. One variation that is not discussed herein is the construction of the vault within a mined cavity or tunnel. This concept is more appropriate to the mined cavity alternative, considered separately. Figure 4 illustrates construction of disposal vaults into a hillside with access through door openings in the walls.

(1) Excavation. The size of excavation required for construction of a belowground vault is dependent upon the physical size and topography of the disposal site, and the projected volume of waste to be disposed. The depth of excavation must be site-specific and depends primarily upon the depth to the groundwater table, depth to bedrock, thickness of cover desired, and stability of the sidewalls. A typical trench excavation is shown in Figure 5a. Figure 5b shows a cross-section of a vault excavation and other components of the disposal vault. Note that the excavation slopes to a French drain on one side for collection and drainage of infiltrating water.

(2) Drainage layer. A drainage layer below the vault foundation and around the vault walls may not be required or desirable under some conditions. If a drainage layer is specified, it should be designed for long-term performance. The drainage layer should be graded to consist of various grain sizes to

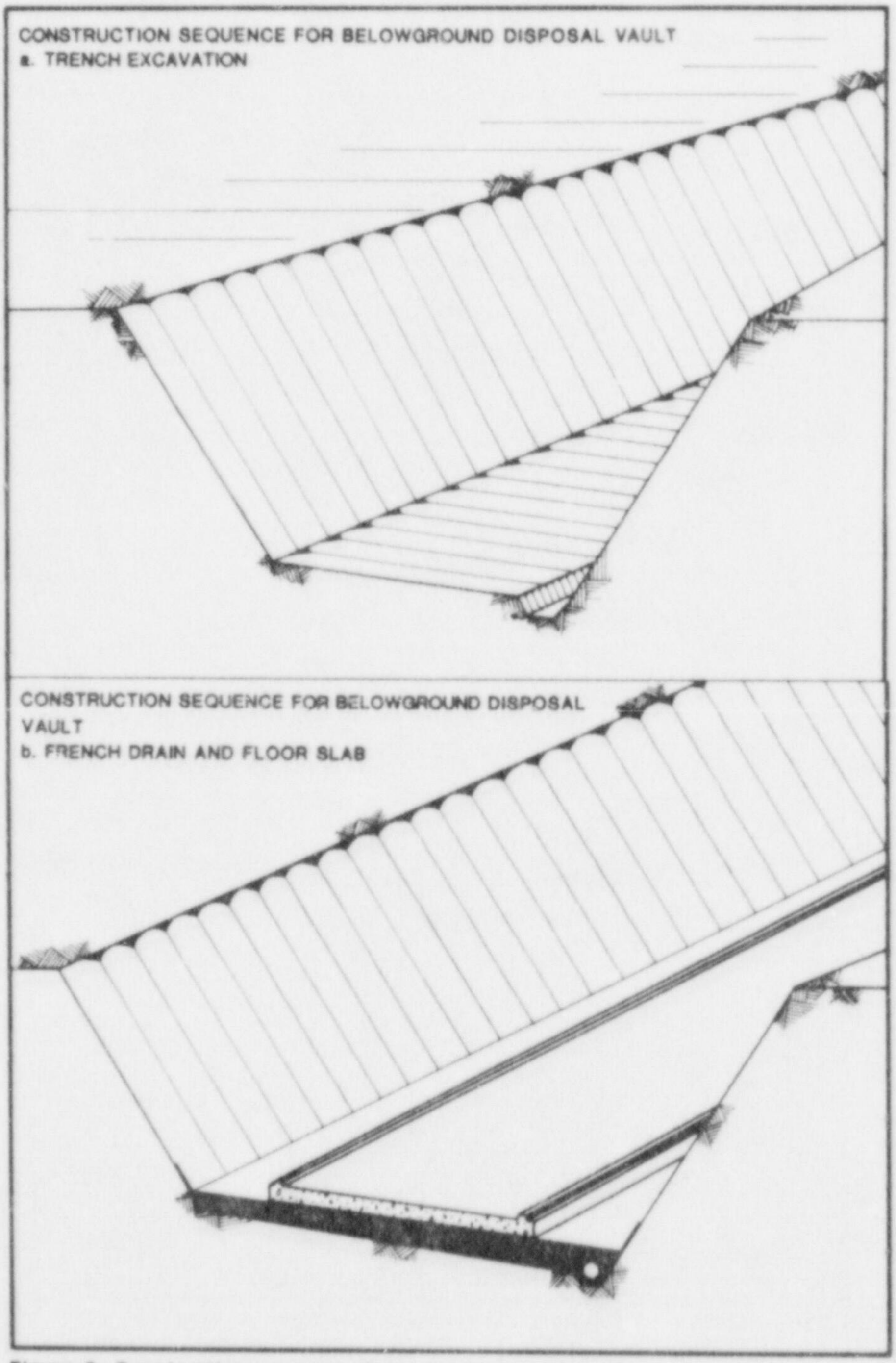


Figure 5. Construction sequence for cut and cover construction of belowground vault LLW disposal units. Figure 5a. shows the initial excavation. Figure 5b shows the underdrainage system and floor slab in place.

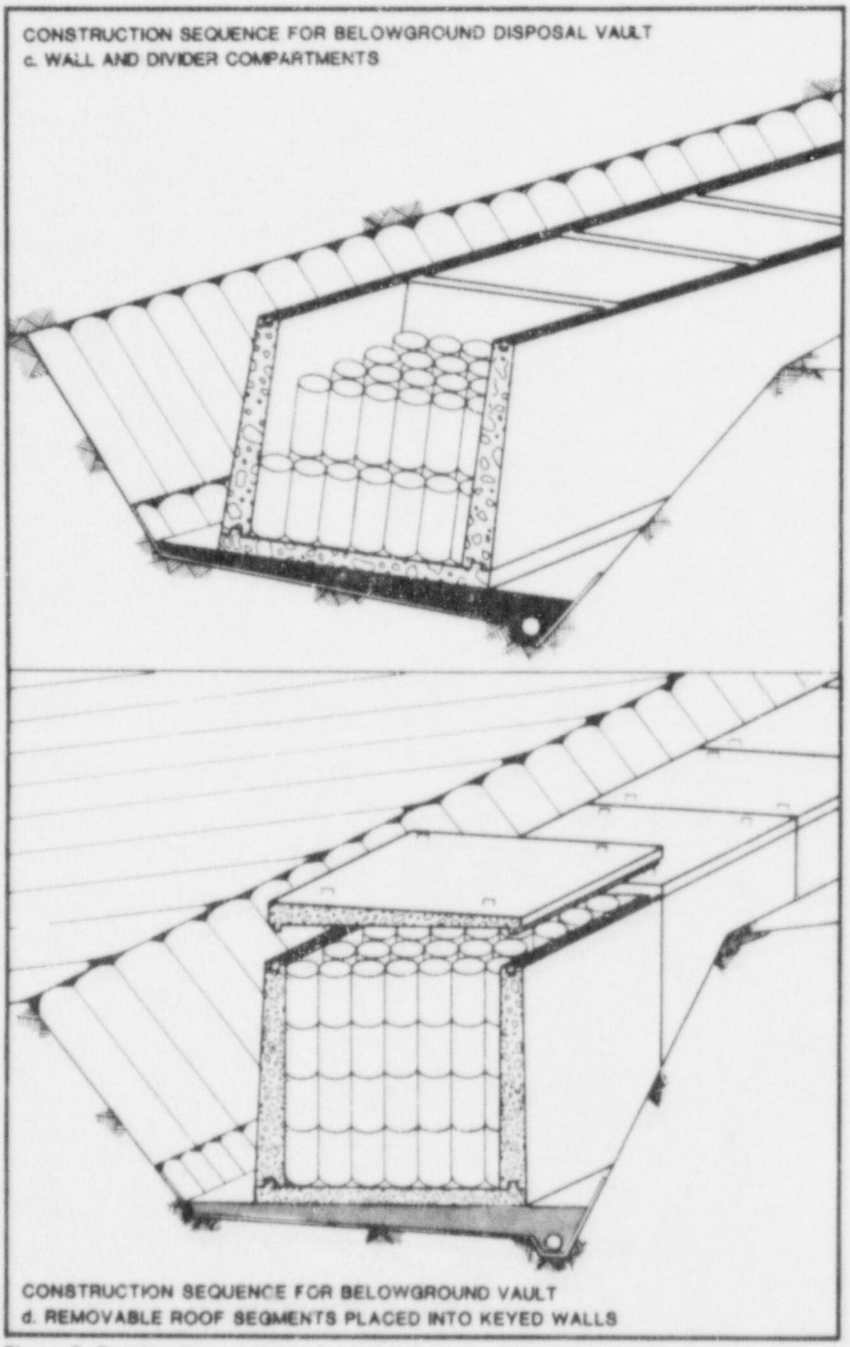
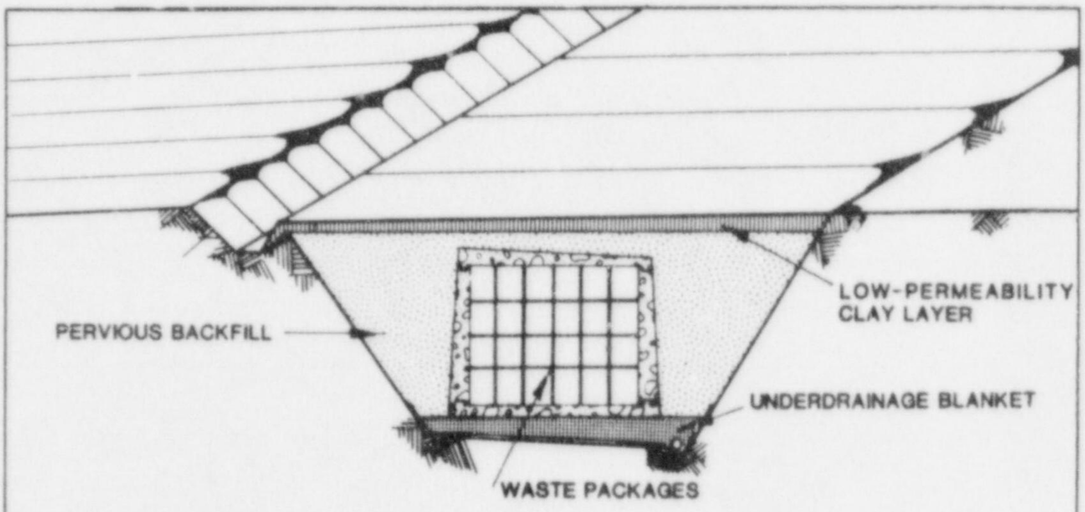
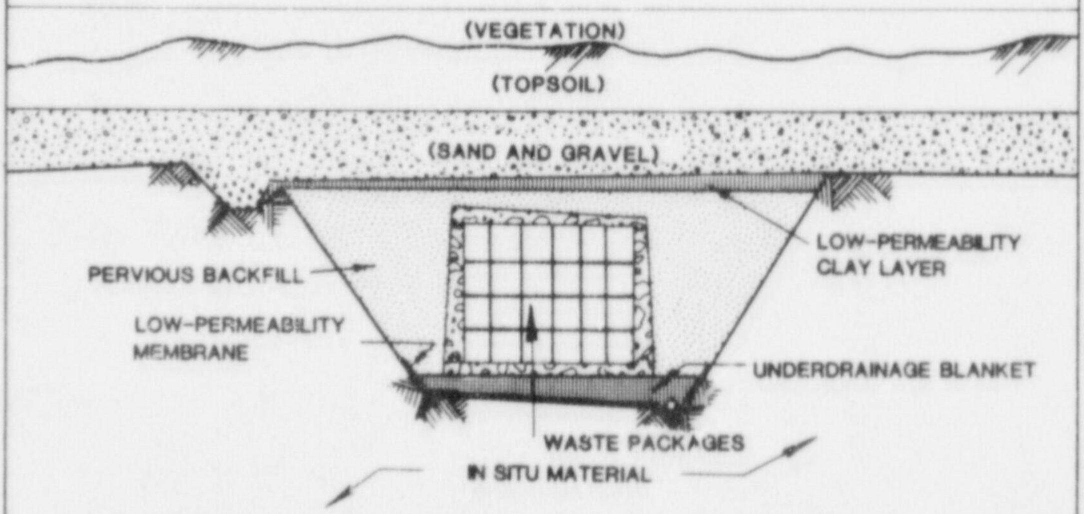


Figure 5. Construction sequence for cut and cover construction of belowground vault LLW disposal units. Figure 5c shows the compartmentlized vaults constructed within the excavation. Figure 5d shows the removable roof segments placed into keyed walls.



Construction sequence for belowground disposal vault
e. Waste-filled vault with pervious backfill placed around vault. Next a low-permeability clay is placed that covers trench excavation and slopes toward surface drainage ditch



Construction sequence for belowground disposal
f. Low -permeability clay layer covered with pervious fill, then topsoil and vegetation. Vault is now considered closed.

Figure 5. Construction sequence for cut and cover construction of belowground vault LLW disposal units. Figure 5e shows the waste filled disposal vault with roof in place and pervious backfill placed around vault. A low-permeability clay layer is shown above the pervious material above the vault roof. In Figure 5f the low-permeability layer has been covered with a pervious drainage layer, topsoil, and vegetation.

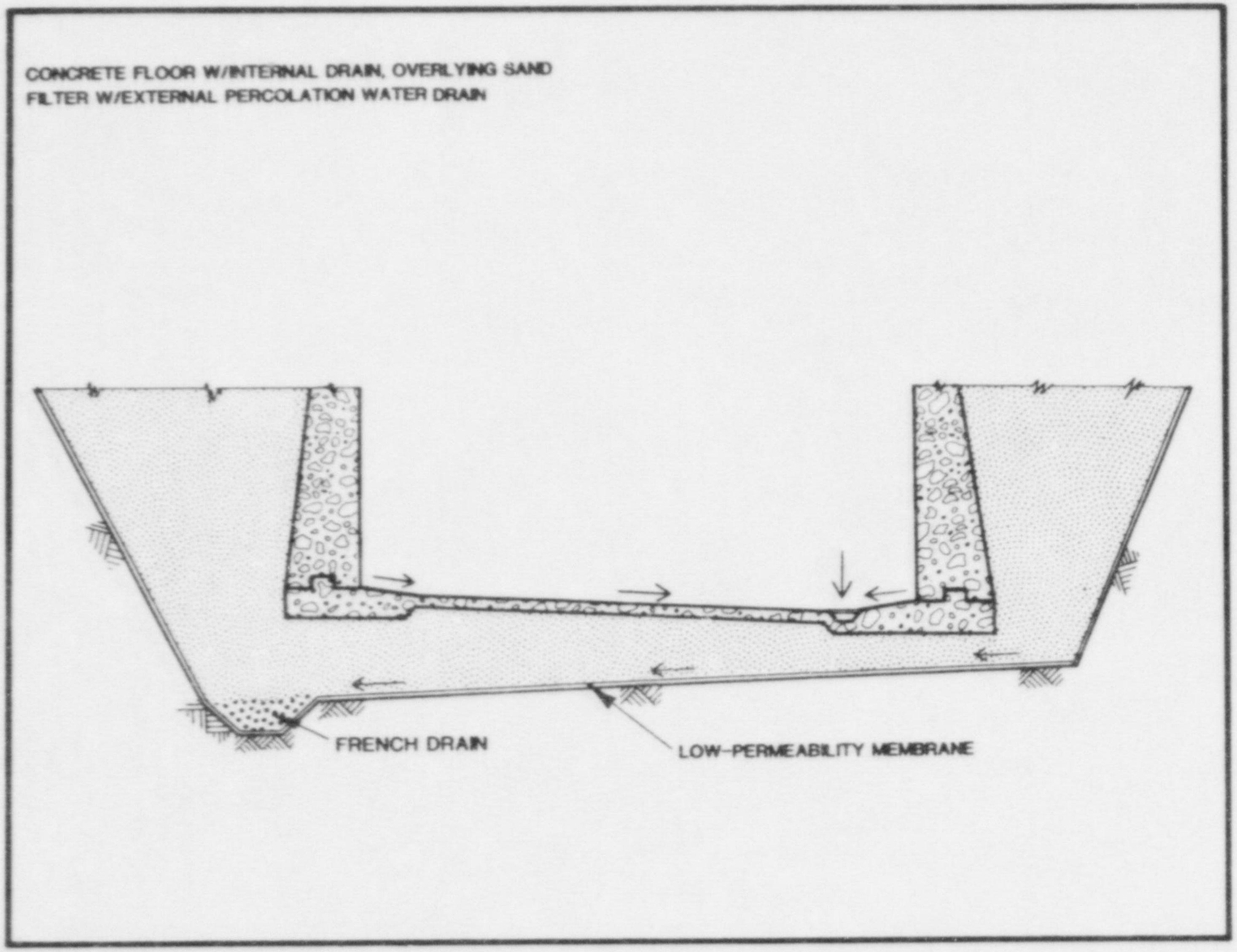


Figure 6. Cross section of belowground vault, drainage layer and vault slab and foundation.

prevent migration of fines from the cut slope into the blanket. Migration of fines into the drainage blanket would clog the blanket or reduce its efficiency. The drainage layer should be compacted to form a stable base for the vault foundation and slab. Poor compaction could result in excessive total or differential settlement, which could in turn result in structural distress to the vault and damage to drains and monitoring wells. Figure 6 shows a cross-section of the lower portion of a belowground vault, drainage layer, and vault slab and foundation. As mentioned above, the drainage layer should be constructed over a sloping excavation to promote drainage and collection of water.

(3) Vault floor. The vault floor may be natural or treated geological materials or engineered materials. Figure 5b shows a concrete floor slab cast over the drainage blanket. Figure 6 is similar but shows a thickened footing section at the slab edges to support the walls. The slab may be provided with an interior drain as shown in Figure 6 which would drain to an exterior monitored sump by gravity before discharge.

Figures 7a and b illustrate two alternative vault floor concepts. In Figure 7a the vault floor is natural soil. A coarse-grained soil floor is shown in Figure 7b underlain by a membrane and French drain, which would lead to an exterior, monitored sump. The possible advantages of the floor system shown in Figure 7b are first, the provision of a free-draining material beneath the waste packages, which would minimize the contact of infiltrating water with the wastes, and second, elimination of a concrete slab, which would result in economy of construction while minimizing the possibility of free water collecting in the disposal unit. The design philosophy for both concepts (Figures 7a and b) is that any water that infiltrates through the roof or walls of the vault should have an avenue of escape. In these examples, the avenue of escape is a floor of material with greater permeability than that of the roof or walls. If a concrete slab floor is used, the drain provides the avenue of escape. If no drain is provided, the drainage layer surrounding the vault must be designed to channel any seepage from within the vault to the French drain beneath the vault floor.

(4) Vault walls and roof. The belowground vault must support, in addition to its own weight, the loads imposed by construction and waste-emplacement operations (live loads) and the loads imposed by backfill placed around and over the vault (dead loads). Figures 5c and 5d illustrate a diaphragm concept for walls and roof, in which the concrete walls are keyed into the slab and the removable roof segments are keyed into the walls. Figures 7a and b illustrate a different concept in which the massive walls are designed to act as individual retaining walls to resist lateral backfill loads.

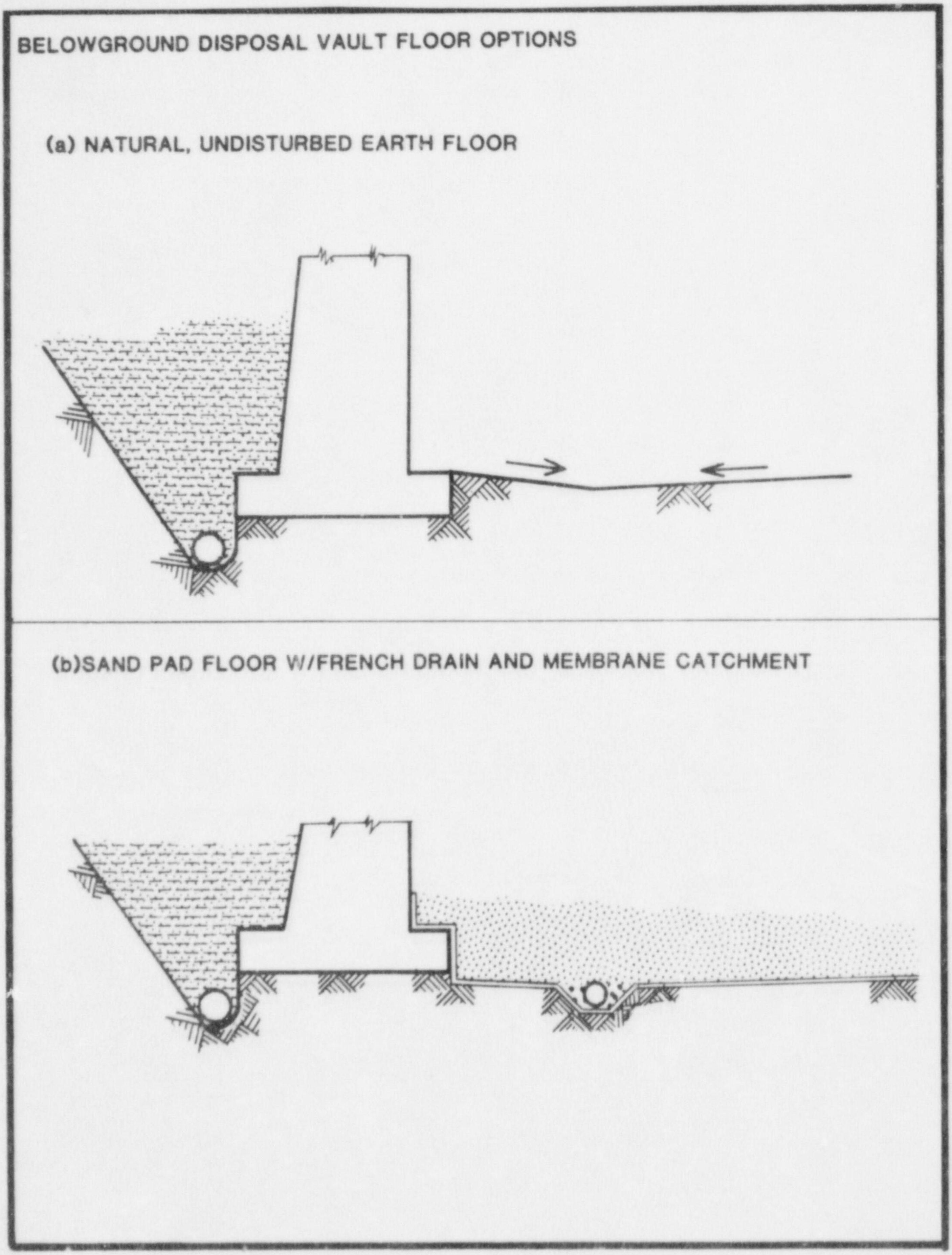


Figure 7. Alternative belowground disposal vault floor options, using natural soil in Figure 7(a) as the vault floor and coarse grained soil in Figure 7(b).

(5) Backfill. Backfill may be placed around the vault before or after placing waste packages in the vault. Efficiency of operations is the probable deciding factor for this choice. If backfill is to be placed around the waste packages inside the vault, and wastes are placed through openings in the roof, then it may be convenient to place backfill around the vault at the same time backfill is placed around the wastes. This option has the added advantage of reducing net lateral loads on vault walls by balancing the loads inside and outside the walls. However, this method would require a crane with longer reach to operate a safe distance from the edge of the excavation.

If backfill is placed around the vault before waste packages are placed, a smaller crane may be used. However, the walls must be designed to resist higher lateral loads in this case.

Regardless of the method of backfill placement, in the authors' opinion, the backfill material should be free-draining and graded to resist migration of fines into this drainage blanket. Use of low-permeability backfill is not recommended. This type of backfill may migrate downward into the subfloor drainage blanket and clog it or reduce its efficiency.

For the vault concept shown in Figure 4, with access through doors in the walls, the backfill may be placed before or after waste emplacement. No particular advantages are envisioned for either choice.

(6) Vault interior drains. As discussed in the previous section on vault floors, the interior drain provides an avenue of escape for any water that enters the vault or results from decomposition of wastes within the vault. An interior drain also provides a means of monitoring the vault and could provide an early warning against unacceptable radionuclide releases inside the vault. The drain should pass the effluent to a monitored sump for this purpose, before the water is discharged. Monitoring plans should take advantage of these drains, and specific remedial-action plans should be keyed to measured unacceptable levels of radionuclides in the effluent.

(7) Vault cover. The vault cover should serve the same purpose as the cover for a shallow land burial facility. The cover should minimize infiltration of surface water, provide additional shielding of the wastes from man and the environment, and prevent intrusion of plants or animals into the wastes. The cover includes the vault roof and soil fill above the vault roof. The roof should be sloped or crowned to enhance drainage away from the vault. Figure 8 illustrates one concept for a vault cover using a combination of engineered materials and soils to minimize infiltration, provide for drainage away from the vault, and resist erosion. This concept uses a low-permeability membrane directly over the vault roof, overlain by a layer of low-permeability clay. A pervious drainage layer

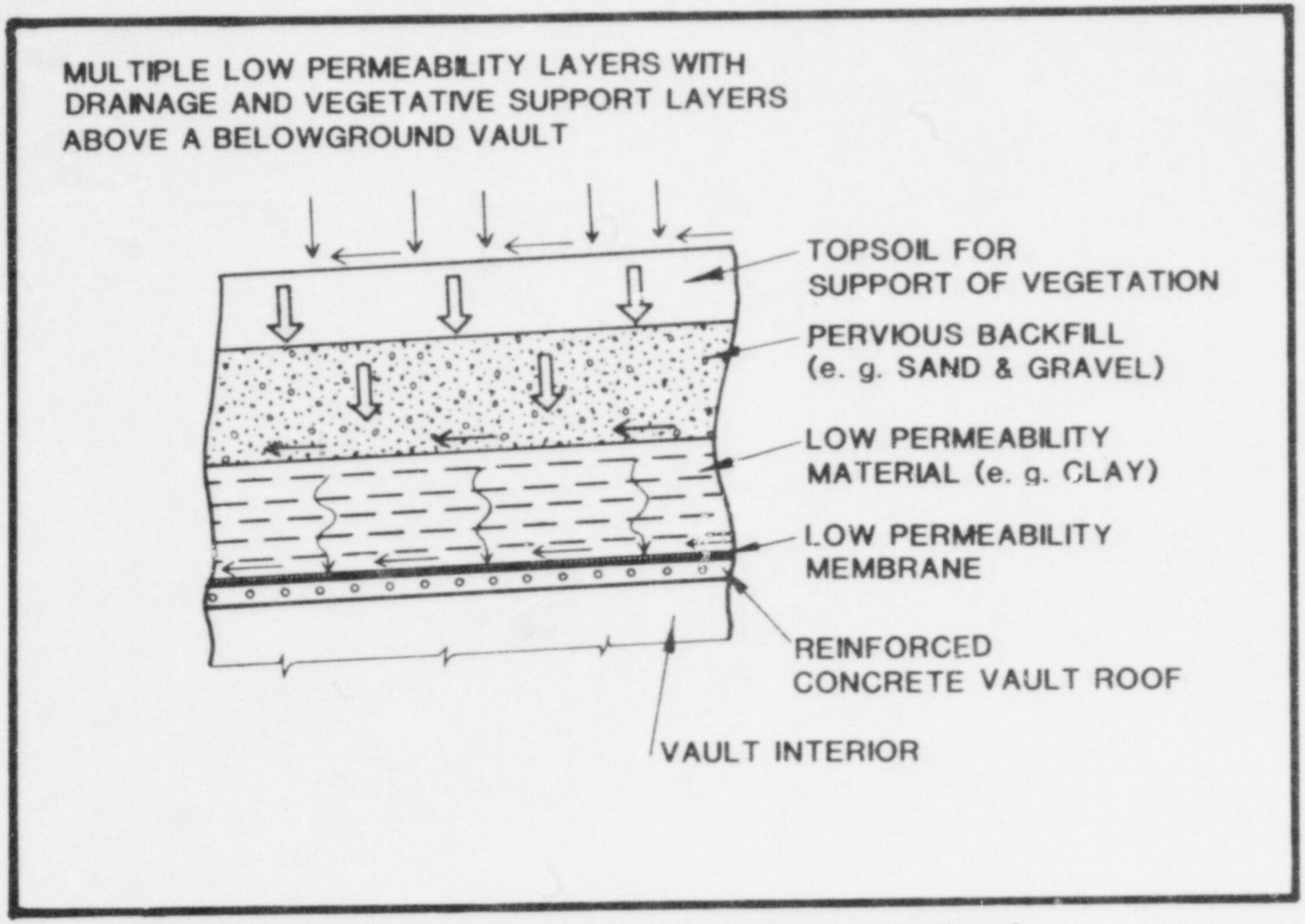


Figure 8. One concept for LLW disposal vault roof cover using a combination of engineered materials and soils to minimize infiltration and provide for drainage away from the vault.

is placed over the clay layer and is covered with topsoil, which is seeded.

Some researchers (Dehmel et al., 1984) have suggested an alternative cover which relies on the "wick effect." With this system the relative order of placement of the pervious and "impervious" layers are reversed. A distinct boundary between these layers must be maintained for the system to work. Normally a layer of filter cloth would serve as the boundary. It is claimed that the higher soil suction in the low-permeability layer results in lateral movement of the water through this layer to the drains surrounding the vault walls. The proponents claim that the pervious layer above the vault will not become saturated.

In arid regions where establishment of a vegetative cover may be difficult, a layer of various size stones or gravel may be substituted to help resist erosion.

2.4 Performance Capabilities

A belowground vault has several performance capabilities that make it an attractive LLW disposal alternative.

a. The vault is visually unobtrusive.

b. Intrusion of ground water, animals and plants into a belowground vault is unlikely. The belowground vault is itself a barrier to intrusion in addition to the natural barrier of subsurface geologic materials.

c. Inadvertent human intrusion into a vault is highly unlikely both because of its structural competence and its obvious contrast with earth materials.

d. A vault is self-supporting and can support an earth cover with negligible subsidence or deformation.

e. Escape of liquid or gaseous matter from the vault is impeded by the vault structure and the surrounding earth cover. Radiation flux to the surface is limited by the engineered roof and by the earth cover.

f. An appropriately designed vault should remain intact and sealed through all foreseeable or projected seismic, meteorological, and earth movement events. In the event of erosion or mass earth movement, the vault may become exposed but the waste would still be isolated.

g. The vault units would be easy to locate and could be reentered in the event the waste material is to be retrieved.

h. Design and construction of the vaults could be standardized for a particular site with potential economic benefits. Standardization of the vaults could lead to standardization of waste handling procedures. Uniformity of facilities and procedures could decrease vulnerability of workers to radiation exposure caused by accidents while performing unfamiliar activities.

Some disadvantages are associated with belowground vaults for LLW disposal.

_i_. The vaults must be protected from flooding during construction and operations.

_j_. They cannot be visually inspected or monitored.

_k_. Use of remote handling facilities is hampered by the limited access. Consequently, exposure of workers to radiation hazards may be higher than desirable for other alternative methods.

3. TECHNICAL REQUIREMENTS FOR BELOWGROUND VAULT DISPOSAL OF LLW

In this section, the technical requirements thought to be necessary for evaluation of site suitability, design, operations, closure, and monitoring are developed.

The pattern of development used for each section is:

a. First, each existing criterion for near-surface disposal is quoted, including the subparagraph number of 10 CFR 61 Subpart D under which it appears.

b. The criterion is discussed and judged as to its relevance to belowground vault disposal.

c. A recommendation is made to:

(1) Retain the criterion as is,

(2) Not apply the criterion to the evaluation of this alternative,

or

(3) Modify the criterion to make it applicable to this alternative.

Any departures or changes in recommendations from the position taken in the Task 1 report (Bennett and others, 1984) are noted. At the end of each section (site suitability, design, operations and closure, and monitoring) technical requirements implied within 10 CFR 61.12 relative to these topics which are not covered by existing criteria or recommended modifications are discussed. Specific criteria in prescriptive language are not given. Rather the points that should be addressed and the reasoning behind them are stated. This method of presentation is thought to be more appropriate than offering specific criteria, as it allows the NRC to consider those issues and develop specific wording that it considers appropriate on a point by point basis.
Alternatively, the NRC may wish to provide regulatory guidance, as appropriate, without changing or adding to the existing criteria.

3.1 Site Suitability

3.1.1 Role of Site Characteristics

Primary emphasis in assessing disposal site suitability is given to long-term satisfaction of the performance objectives of 10 CFR Part 61, Subpart C.

Site characteristics should not only facilitate design and construction, but also promote ease of operations and closure. The primary role of site characteristics, however, will be to promote the stability and isolation of wastes in the event of failure of any system component.

Sole reliance on site characteristics for meeting the performance objectives is not a requirement. Collective use will be made of site characteristics, design features, operations and closure methods, waste-form management, and institutional controls. Since disposal facilities may be constructed in many different geographical areas, it is anticipated that sites will reflect a wide range of geologic, hydrologic, meteorologic, climatic, environmental, and socioeconomic conditions. The contribution of site characteristics toward stability and isolation of wastes, therefore, may vary from site to site.

In general, the reliance which can be placed on design features and maintenance tends to decrease with time after closure. Therefore, tradeoffs related to the degree of reliance placed in site characteristics, design features, or methods of facility operation and site closure should be made with the goal of maximizing the long-term contribution toward public health and safety (Siefken and others, 1982).

Site characterization may be defined as a program of investigations and tests, both in the field and laboratory, undertaken to define the site characteristics affecting the isolation of the LLW and long-term stability of disposal sites. Characteristics of the disposal site and surrounding vicinity which must be determined should include, but not necessarily be limited to, the geological, geomechanical, hydrological, meteorological, climatological, and seismological characteristics.

3.1.1.1 Geological and Geomechanical Characteristics

A regional geological framework, including the stratigraphy, tectonics, structure, and physiography, must be established for a proposed site. Detailed geologic information, required for site modeling, should be obtained by surface mapping, exploratory boreholes, surficial geophysical surveys, borehole geophysical logging, and test pit excavations.

Geomechanical characteristics of the site soil and rock deposits are required for evaluation, as well as design and analyses. Performance parameters such as the coefficient of consolidation, permeability, cohesion, angle of internal friction, unconfined compressive strength, and deformation modulus should be determined, as appropriate, for the soil and rock types. Index properties, such as water contents, unit weights, Atterberg limits, Standard Penetration Test (SPT) blow counts, cone penetration resistance, particle-size distribution, void ratio, organic content, and Rock Quality Designation (RQD) should be determined for classification, as well as design purposes. Bearing capacity and settlement should be predicted from appropriate soil properties, structural loads, and layout.

3.1.1.2 Hydrological Characteristics

Surface water and ground water represent the most significant pathways for potential long-term releases to the general population. Therefore, proper characterization of the hydrological conditions is required, including both site-specific and regional data. Surface water studies should include aerial photography and topographic mapping, as well as the determination of drainage areas, flood flow frequencies, runoff rates, infiltration rates, flow rates, and flow volumes.

To define the hydrological and stratigraphic framework, site characterization studies should be performed to identify and characterize the separate hydrogeologic units underlying the site, including their lithology, thickness, lateral extent, continuity, inclination, areas and modes of recharge and discharge, piezometric levels, hydrochemistry, interrelationship with adjacent hydrogeologic units, and interrelationship with surface water bodies.

The hydrological characteristics of the site should be used to develop flow and transport models with which migration of potential releases may be evaluated. In addition to modeling the surface and subsurface hydrology, ground truth documentation should be obtained by laboratory and field tests. Data collection or sampling points should be established which will not only verify model predictions, but which may continue to be used throughout the design and construction phases and, eventually, for long-term monitoring.

3.1.1.3 Meteorological and Climatological Characteristics

Site meteorological and climatological data are required to determine a water budget, establish the ranges and frequency of occurrence of unusual phenomena, and perform atmospheric dispersion analyses. The NRC staff (Siefken and others, 1982) recommends that an onsite meteorological station should be established and operated a minimum of one year during site characterization to obtain site-specific data. Existing long-term data should be obtained from the National Oceanographic and Atmospheric Administration. The onsite meteorological station should be incorporated into the eventual site monitoring program to verify data used for the evaluation and characterization.

3.1.1.4 Seismological Characteristics

As an engineered structure, a vault may incorporate design safeguards against damage from earthquake-induced ground motions and may be sited in a region of finite risk of earthquake occurrence. This capability is one of the important advantages of an engineered vault for LLW disposal. To exercise the freedom of siting a vault in a certain seismic risk zone, however, it is imperative that the proposed site be characterized in terms of the probable seismically-induced ground motions - their amplitudes, wavelengths, duration, and frequency of probable occurrence. The maximum probable earthquake magnitude and its associated intensity at the site for the life of the radionuclide containment should be used as the prediction earthquake when determining ground motions and survivability of the engineered disposal unit.

3.1.2 Assessment of Existing Criteria

The existing criteria for assessment of near-surface disposal site suitability are contained in 10 CFR Part 61 Subpart D, paragraph 61.50.

Criterion 61.50 (a)(1) states: "The purpose of this section is to specify the minimum characteristics a disposal site must have to be acceptable for use as a near-surface disposal facility. The primary emphasis in disposal site suitability is given to isolation of wastes, a matter having long-term impacts, and to disposal site features that ensure that the long-term performance objectives of Subpart C of this part are met, as opposed to short-term convenience or benefits."

Discussion. Disposal of LLW in belowground vaults is similar in many respects to near-surface disposal in trenches. Consequently, most of the features that would make a site suitable for trench disposal would also make a site suitable or desirable for a belowground vault disposal facility.

The emphasis for site suitability has not changed, nor has the importance of ensuring that long-term performance objectives be met.

Recommendation. This criterion states the goal of all subsequent site suitability criteria. Therefore, the criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(2) states: "The disposal site shall be capable of being characterized, modeled, analyzed, and monitored."

Discussion. This criterion is necessary to ensure that the long-term performance objectives are met. While the wording seems deceptively simple, the underlying issue is not. Many rather clever analytical tools have been developed to model natural systems, e.g., 2-D and 3-D computer simulations for analysis of ground-water movement, and sophisticated analyses of slope stability. However, all models and analyses depend on sound judgment related to model implementation and reliable input data to reach credible solutions.

The NRC staff (Siefken and others, 1982) points out that models tend to homogenize stratigraphic units and average the hydrologic properties to satisfy assumptions and boundary conditions. Therefore, the site characteristics used as model inputs must vary over a sufficiently narrow range so that the simplified inputs and assumptions are valid. Sedlett and others (1982), Cherry, Grisak, and Jackson (1974), and Cherry and Gilham (1977) have discussed this issue and indicated that monitoring to measure the necessary site characteristics is much more complex and less reliable for geologically complex sites. Sedlett indicated that it may be impossible to get adequate, reliable data from sites underlain by fractured rock. Even sophisticated, expensive site investigations only sample a small fraction of the subsurface, so extrapolation over wide areas at highly variable sites is unreliable.

Simply put, the more uniform the site and the natural processes occurring on it, the less complex and costly the site investigation may be, and the more reliable predictions may be.

Recommendation. This criterion should be retained as is.

Criterion 61.50 (a)(3) states: "Within the region or state where the facility is to be located, a disposal site should be selected so that projected population growth and future developments are not likely to affect the ability of the disposal facility to meet the performance objectives of Subpart C of this part.

Discussion. The objectives of this criterion are to minimize the risks of exposure of the general population to releases of radioactivity and to minimize the risks of inadvertent intrusion. The objectives can be met using census data and urban planning studies to develop site-specific population and development projections. However, data and projections from existing planning studies may decrease in reliability as the time period of interest increases.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(4) states: "Areas must be avoided having known natural resources which, if exploited, would result in failure to meet the performance objectives of Subpart C of this part."

Discussion. The goal of this criterion is to avoid the possibility of compromising site integrity caused by future exploration or exploitation of the natural resources adjacent to or underlying the disposal site and minimize the likelihood of inadvertent intrusions. An example would be deep borings for oil exploration. A less obvious example might be a deep water well. Such wells, if pumped at rates much higher than the ground-water recharge rates, can cause surface subsidence and cracking of the surface. This phenomenon is a serious problem in the arid southwestern U. S. and is discussed later in the section on additional technical considerations for site suitability. Practical application of the criterion is not likely to preclude or significantly limit the selection of suitable sites within a given region or state.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(5) states: "The disposal site must be generally well drained and free of areas of flooding or frequent ponding. Waste disposal shall not take place in a 100-year floodplain, coastal high-hazard area, or wetland, as defined in Executive Order 11988, "Floodplain Management Guidelines."

Discussion. The desirability of a well-drained site free of areas of flooding or frequent ponding can be readily understood. Open, flooded excavations would have to be pumped dry. Trench sidewalls might erode or fail by sliding. Equipment could be damaged or immobilized, making it impossible to take damage prevention or remedial measures.

The probability of occurrence and severity of the above problems can be estimated based on the frequency and extent of a flood event at a specific site and use of appropriate hydrological models.

The second part of the criterion, which prescribes avoidance of legally defined flood prone areas, is technically achievable using existing topographic maps and rainfall and runoff data.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(6) states: "Upstream drainage areas must be minimized to decrease the amount of runoff which could erode or inundate waste disposal units."

Discussion. The above criterion has as its primary goal the prevention or minimization of damage from flash flood situations. This situation is more likely in areas of greater topographic relief.

The criterion, therefore, implies that the disposal units should be located on high ground, i.e., the ridgetops and plateaus, but protected valleys or relatively flat lands are not excluded. This requirement is technically sound.

Recommendation. The criterion should be retained as is. The avoidance of inundation is important and the objective of the criterion is valid and achievable.

Criterion 10 CFR 61.50 (a)(7) states: "The disposal site must provide sufficient depth to the water table that ground-water intrusion, perennial or otherwise, into the waste will not occur. The Commission will consider an exception to this requirement to allow disposal below the water table if it can be conclusively shown that disposal site characteristics will result in molecular diffusion being the predominant means of radionuclide movement and the rate of movement will result in the performance objectives of Subpart C of this part being met. In no case will waste disposal be permitted in the zone of fluctuation of the water table."

Discussion. The goal of this requirement is to avoid contact of waste packages and ground water. Ground water is considered to be the major pathway of release in humid areas. Contact of ambient ground water and waste packages also hastens the rate of package deterioration and radionuclide migration. The criterion does not specify the depth between the water table and the disposal unit. This depth must be determined from measurement and analysis of site characteristics. These characteristics include the coefficient of permeability, the degree of homogeneity of the site soil and rock deposits, whether preferential flow paths exist, and the degree of fluctuation of the water table. The impacts of present and projected land uses on the regional water table should also be considered in addressing this criterion.

The criterion provides a possible exception for construction of a disposal unit below the water table, specifically avoiding the zone of fluctuation. In the authors' opinion, it is conceivable that a suitable disposal site could be located, such that disposal below the water table would pose no higher risks and perhaps lower risks than disposal above the water table. However, the evidence required to demonstrate this would have to be quite reliable to withstand the intense scrutiny it would receive.

The NRC staff (Siefken and others, 1982) discussed the conditions that should be met for conclusive evidence that molecular diffusion is the predominant means of radionuclide movement. They suggested the use of age-dating of ground water as one method for this purpose and discouraged the use of more common methods such as pumping tests or pressure injection tests as being inapplicable for very tight formations.

Cherry and Gillham (1977) argue that molecular diffusion can be demonstrated conclusively for certain very low permeability thick clay deposits below the zone of weathering. They believe that waste disposal in such deposits below any aquifers used for water supply offers the best option for long-term waste isolation in Canada. They offered three hydrogeologic criteria to support site suitability. The criteria are that the site should:

a. Be geomorphically and seismically stable.

b. Be such that adequate burial space can be created at a significant depth below the level of active water table fluctuation in a zone where the rate of hydraulic flow of ground water is negligible in comparison to rates of molecular diffusion.

c. Be such that the burial space can be located in a position within the regional ground-water flow system that, in the event that radionuclide leakage occurs, would prevent contamination of aquifers used for water supply and which would tend to prevent migration of radionuclides into the biosphere.

Diffusion-controlled transport zones were judged to be acceptable because diffusion is an extremely slow process, with radionuclide concentration as its driving mechanism. This disposal option was judged to be much more desirable than burial in or near the zone of ground-water fluctuation. Cherry and Gillham (1977) suggested age dating of ground water by measuring the distribution of natural isotopes such as ^{3}H, ^{18}O, and ^{14}C to determine whether fractures present significant transport pathways. They did not, however, rule out or discourage disposal above the water table and zone of fluctuation. They suggested a minimum distance of 6 to 8 meters above the average water table depth. However, their attempts to apply this criterion and other important technical considerations led them to conclude that searches for suitable sites for disposal above the water table were futile in southern Canada.

In summary, the prime goal of the criterion to minimize contact of moving water with wastes can be achieved either by maintaining a sufficient distance between the wastes and ground water or by disposal in very low permeability deposits within the zone of ground-water saturation.

Recommendation. The criterion is applicable to disposal of LLW in below-ground vaults and should be retained as is. Since the ground-water pathway is so important in the assessment of disposal site performance in humid regions, this criterion is considered to be a crucial test for site suitability.

Criterion 10 CFR 61.50 (a)(8) states: "The hydrogeologic unit used for disposal shall not discharge ground water to the surface within the disposal site."

Discussion. Location of a disposal unit in a formation that discharged ground water to the surface within or even near the site should be considered unsafe and unnecessary. It is relatively simple to uncover evidence of springs early in the site investigation. Such occurrences should be grounds for exclusion of that particular site from further consideration.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(9) states: "Areas must be avoided where tectonic processes such as faulting, folding, seismic activity, or vulcanism may occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts."

Discussion. The performance objectives to which this criterion refer are equally applicable to any LLW disposal alternative. However, the degree to which seismic activity might impair disposal site performance would vary significantly for different disposal concepts, or even for the same alternative, if built to withstand different design basis natural events.

Appropriate design features of a belowground vault may allow favorable determination of suitability of a site for areas demonstrating various degrees of seismic intensity. For those cases where resistance to tectonic forces is included in the design, the site characterization must include determination of the maximum probable seismic event in terms of accelerations, particle velocities, and wavelengths of the vibrations.

Krinitzsky and others (1973-1985) and Boore and others (1978) describe the evaluation and assessment process necessary to define seismic risks at a locality. Coulter and others (1972) and Allen (1976) describe site-specific geologic considerations in earthquake hazard analysis. Newmark and Rosenbleuth (1971), Newmark and Hall (1973), and Dowrick (1977) describe procedures for designing seismic hazard resistance into belowground structures. The state-of-the-art exists in both engineering design and construction practice to utilize LLW disposal sites that demonstrate finite (greater than zero) levels of seismic hazard without compromising satisfaction of the Subpart C performance objectives. The key to the use of such sites for belowground vault disposal units is reduction of the uncertainties of reliance on in situ materials for containment. Because a disposal unit is essentially a passive structure, compared to an active structure like a nuclear power plant, there is more freedom in exercising engineering designs to allow use of sites having some finite level of seismic hazard. Since the disposal site is defined in 10 CFR 61.2 to consist of the disposal units (in this case vaults) and buffer zone, the objective of the criterion could be met using appropriate seismic design and construction methods for the vaults. Consequently, the criterion is directly applicable.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.50 (a)(10) states: "Areas must be avoided where surface geologic processes such as mass wasting, erosion, slumping, landsliding, or weathering occur with such frequency and extent to significantly affect the ability of the disposal site to meet the performance objectives of Subpart C of this part, or may preclude defensible modeling and prediction of long-term impacts."

Discussion. The goal of this criterion is valid. Serious erosion could uncover the vault if left uncorrected. Slumping soils and landslides could cause structural distress and damage drainage layers or monitoring wells. Weathering of site geologic materials can result in swelling and increased erosion. Areas undergoing rapid geological processes can usually be identified during the screening process through analysis of aerial photographs taken a few years to tens of years apart. Such areas can be eliminated at this stage without seriously limiting the availability of suitable sites within a state or region.

Recommendation. The criterion should be retained as is. This recommendation differs from the position stated in the Task 1 report (Bennett and others, 1984). Recommended modifications to address subsurface geological processes mentioned in the Task 1 report are discussed in section 3.1.3 below. These matters are not properly described as surface geological processes.

Criterion 10 CFR 61.50 (a)(11) states: "The disposal site must not be located where nearby facilities or activities could adversely impact the ability of the site to meet the performance objectives of Subpart C of this part or significantly mask the environmental monitoring program."

Discussion. This requirement is generally applicable to any LLW disposal facility. It does not preclude selection of a disposal site near other facilities. It does require an assessment of the potential adverse impacts of such a decision. This assessment can only be made on a site specific basis.

Recommendation. The criterion should be retained as is.

3.1.3 Suggested Additional Technical Considerations

Additional technical considerations for demonstrating site suitability should include requirements to determine the existence and potential adverse impacts of dispersive soils, liquefiable soils, corrosive soils, expansive soils, karstic or cavernous areas and areas of land subsidence at a potential disposal site. The potential problems caused by occurrence of such deposits are discussed below.

3.1.3.1 Dispersive Soils

The occurrence of dispersive soil deposits surrounding or near the disposal site can result in accelerated erosion, piping, and collapse of the surface.

Pinhole erosion tests can provide evidence of the susceptibility of soils to dispersion (Sherard and others, 1976). High percentage (greater than 60 percent) of sodium in total dissolved salts is also an indicator of dispersive clays. Dispersive soils cannot be identified by conventional index tests such as Atterberg limits or particle size distribution (Perry, 1979). Visual inspection of cut slopes and embankments can uncover dispersive soil problems. Visual inspection is not very helpful for undisturbed sites because dispersive clays are usually not present in topsoil due to the process of eluviation (movement of clay particles downward in the soil profile). Therefore natural deposits may show little or no evidence from surface appearance that the underlying soil may be dispersive. The piping channels that develop in the underlying soil can be obscured by the vegetative cover and bridging of the topsoil deposit. Eventually, this top layer will collapse into the hole as erosion damage progresses. In excavated slopes and man-made embankments, dispersive characteristics are more readily observable. Excavated slopes in dispersive clays exhibit rill erosion, surface cracking, and vertical erosion tunnels resembling badlands topography (Perry, 1979). Embankments constructed of dispersive clays, even with good vegetative cover, also develop rainfall erosion tunnels called cave-ins or jugs. In the authors' opinion, the primary risk to disposal vaults constructed in dispersive soil is from piping erosion. If the dispersive material is used for the backfill placed around the vault, interconnected cracks and voids could provide preferential paths for infiltrating water. These paths could become much larger with time as water erodes the cracks further. If the infiltrating water exits through a shrinkage crack or subsurface erosion channel along the side slope of a ridge, the erosion could lead to local instability of the slope and ultimately to failure.

Measures are available to avoid problems if the dispersive nature of the soil is recognized before construction. For example, sand filters can be used to seal and safely control leaks in dispersive clays. Lime treatment has also proved effective in reducing tunnel erosion in dispersive-clay dams (Forsythe, 1977; Phillips, 1977; and Rosewell, 1977). The calcium in lime is believed to result in a significant reduction in shrinkage and a lower percentage of exchangeable sodium (and a higher percentage of exchangeable calcium) actually going into solution, thereby reducing the dispersive erosion.

3.1.3.2 Corrosive Soils

The occurrence of corrosive soils in humid areas could result in deterioration of disposal-unit barriers, e.g., concrete vault walls, floors, roofs, drains, and waste packages. The potential risk from corrosive soils is much smaller in arid regions.

Corrosion of metallic structural assemblies in the floors of vaults or in ancillary drains or other subsystems of LLW disposal sites may be seriously accelerated by corrosive soils, if present. Pitting and weakening of concrete is one potential adverse effect of corrosive soils. Metallic corrosivity of site soils will be most serious in the presence of high soil electrical conductivities, substantial soil moisture and high dissolved ion contents. 'Corrosion' of concrete is less of a galvanic phenomenon and is better classed as an aqueous chemical solutioning. High soil acidities (low pH), substantial soil moisture, and low concentrations of dissolved calcium ions contribute to long-term concrete 'corrosion.'

Chemical analyses can be used to determine whether a potential problem exists. If so, design and construction measures can be implemented to reduce the impact such as the use of sulfate resistant concrete. Appendix A gives more details about preventive measures that can be taken with regard to corrosive-soil problems. In the authors' opinion, otherwise suitable sites should not be disqualified on the basis of occurrence of corrosive soils alone.

3.1.3.3 Solution Cavities

Solution cavities are formed in carbonate and sulfate rocks such as limestone, dolomite, marble, and gypsum by the action of slowly moving ground water, which dissolves the rock, first to enlarge fractures and then to form tunnels and caves. Most of the caves in the world, including the largest, are of this type. A general term for regions where such phenomena are common is "karst." Disposal in hydrogeologic units above carbonate formations that are actively being dissolved should be avoided. Solution cavities can result in collapse of overlying strata which serve as aquicludes, and ultimately, in distress of vault foundations.

The occurrence of solution cavities can also result in significant unpredictable alteration of ground-water seepage patterns and quantities which would preclude reliable modelling. Because of their discrete locations, the probability of locating solution cavities through normal site investigations is low. Geophysical methods have been successful in some cases. With borings, it is literally a hit or miss situation. Obviously, the probability of missing an existing cavity is higher than that of hitting it. Even if they are reliably located, solution caverns must be grouted to fill the voids. It is costly and difficult to fill completely all voids and impossible to ensure that solutioning will not continue adjacent to the grouted interface.

Regional geological data can provide general evidence to indicate the occurrence, depth, and lateral extent of formations known to be susceptible to occurrence of solution cavities. These karstic areas should in general be avoided.

3.1.3.4 Liquefiable Soils

Liquefaction of soils is the transformation from a solid to a liquified state as a consequence of increased pore water pressure and consequent loss of effective shear strength. Liquefaction of sand deposits has caused extensive damage in numerous seismically active areas of the world, e.g., Japan, Alaska, and California. Less publicized cases of liquefaction of sensitive clays have also caused extensive damage in Norway where marine deposits have liquefied after only minor disturbances. These occurrences were preceded by leaching of salts in the clay by ground water moving downward from mountainous areas to the sea. These clays lose strength as the salts are removed, and in many locations near the sea, a state of near equilibrium exists. Even minor disturbances, such as excavating a building foundation or farm pond, have been known to initiate liquefaction of these deposits. Once started, wide areas can be progressively affected.

The potential risk to LLW disposal facilities from liquefaction is small because most sites with liquefiable deposits have other characteristics that make them undesirable. For example, the site may be near a coastal high hazard area or area of high soil permeability. The main danger would be the failure to recognize the liquefaction potential of deposits below the disposal vault.

3.1.3.5 Expansive Soils

Volume change of expansive soil subgrades resulting from moisture variations frequently causes severe pavement damage. Highways constructed in the Southwest, Western Mountain, Central Plains, and Southeast geographical areas are particularly susceptible to this type of damage.

A 1972 survey (Lamb and Hanna, 1973) of all the 50 states, Puerto Rico, and the District of Columbia indicated that 36 states have expansive soils. Expansive soils are so areally extensive within parts of the US that alteration of highway routes to avoid the material is virtually impossible.

The annual cost of damage to streets and highways caused by expansive soils was estimated in 1973 to exceed $1.14 billion (Jones and Holtz, 1973).

Additional damage to slab-on-grade buildings was not estimated but was and is substantial.

Although this damage is of much concern to state and Federal highway officials and local building officials, expansive-clay problems do not occur in every state. Likewise, problems do not occur uniformly over areas in which expansive soils are found. The key geological factors in determining a geologic unit's expansive nature or "swell potential" are clay mineralogy and amount of clay or shale within a geologic unit. Clay mineralogy, specifically montmorillonite content, can be used to estimate the degree of expansiveness, whereas the frequency of occurrence can be related to the amount of clay or shale in the geologic unit (Snethen, 1979a, 1979b).

One other essential factor that determines whether expansion actually occurs is the availability of water. Without water the soil will not swell. Likewise, if water is available year round, the soil will swell to its full potential under existing loading conditions and no further volume change will occur. Consequently, the problems caused by expansive soils occur primarily near the surface within the zone of seasonal soil moisture changes.

Damage usually takes the form of buckled, warped, and heaved slabs, cracked masonry walls, and general distortion of the structure. For the case of engineered disposal facilities, damage is likely to occur if concrete slabs or walls are cast in direct contact with expansive clays. The potential for damage is exacerbated if the slab is cast over an excavation, because the soil has been unloaded by the excavation and the moisture equilibrium has been disturbed.

Methods are available to minimize or prevent damage from expansive soils. For example, form voids made of heavy corrugated paper are sometimes used beneath slabs to allow space for the soil to swell without damage. The slab must be supported on reinforced grade beams, founded on piers that extend below the zone of seasonal moisture change. The grade beams must not be in direct contact with the surface soil. End-bearing piers founded within the zone of moisture change may heave upward because of the high swelling pressures. The opposite problem of piers settling significantly because of negative skin friction as the clay desiccates during dry periods can also occur. This problem can be dealt with by providing a low-friction membrane between the pier and soil to reduce skin friction.

However, all the engineering fixes have two things in common. They rely on discovery of the expansive nature of the soil before construction and they add to the construction cost.

The Federal Highway Adminstration has published a series of reports describing research conducted to identify problem areas within the US and to develop remedies where feasible (Snethen and others, 1975; Patrick and Snethen, 1976; Snethen, Johnson and Patrick, 1977a, 1977b; Snethen, 1979a, 1979b). These reports describe methods to characterize the potential for volume change, and provide maps showing the occurrence and distribution of expansive soils in the US. In these reports, methods are also recommended for minimizing damage from such soils.

3.1.3.6 Land Subsidence

Subsidence is caused by densification of earth materials, collapse of subsurface cavities, plastic outflow of weak materials, and regional downwarps. There are several causes of densification of earth materials. They are withdrawal of ground water or petroleum, irrigation of old mudflows, vibration of granular materials, densification of deltaic deposits, decomposition of organic materials in swamp deposits, artificial compaction of fills and embankments, and surcharging. Collapse of subsurface cavities may occur in karst topography or because of previous mining activities. Examples of plastic outflow of weak materials can be found where fill has been placed above peat bogs and recent lake deposits. Regional downwarps are large-scale subsidence basins and are caused by tectonic, glacial or volcanic activity.

Subsidence is a gravity-dominated movement, so its principal movement is vertical, but there is always lateral strain associated with subsidence, and this strain could cause serious damage to engineered disposal units. In some areas land subsidence has progressed to the point of equilibrium under existing conditions and any further movement would be relatively insignificant, unless the driving forces changed. Equilibrium would have to be established for the site to be suitable. Subsidence caused by underground cavities can be reduced by grouting the cavities. However, this is an expensive operation and is not recommended if the site can be avoided.

Regional geological data should be carefully examined to identify any areas of possible subsidence. Records of any previous mining, oil drilling, or substantial ground-water use should be investigated. These areas should be avoided if evidence of significant ongoing subsidence is found.

3.2 Design

3.2.1 Role of Design Features

The role of design features is to complement the natural characteristics of the disposal site. The degree of reliance that must be placed in the design features will vary from site to site and even within a site. Design features should not be viewed as a means to overcome a site deficiency, unless it can be shown that the design feature will be effective over the entire time period of concern. Rather the design features should enhance or improve the performance of a site deemed to be satisfactory.

Design features include all the components, equipment, and facilities, other than the land itself, used for waste management and disposal at the site. One goal of the design should be to minimize the potential conflicts between construction, operations, and closure activities to ensure compatibility while providing for efficient land use. Design considerations for major components were discussed in Part 2 of this report.

3.2.2 Assessment of Existing Criteria

The existing criteria for assessment of near-surface disposal-site design are contained in 10 CFR Part 61 Subpart D, paragraph 61.51. Six technical requirements are listed under subparagraph 61.51(a).

The criteria are considered one at a time in the following paragraphs. Additional technical considerations that should be addressed are discussed at the end of the section.

Criterion 10 CFR 61.51 (a)(1) states: "Site design features must be directed toward long-term isolation and avoidance of the need for continuing active maintenance after site closure."

Discussion. The objective of this requirement is technically sound. Major features and components of a belowground vault facility that could enhance long-term isolation of wastes and minimize the need for continuing active maintenance have been discussed in the preceding section of this report.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.51 (a)(2) states: "The disposal site design and operation must be compatible with the disposal site closure and stabilization plan and lead to disposal site closure that provides reasonable assurance that the performance objectives of Subpart C of this part will be met."

Discussion. The criterion is directly applicable to the belowground vault disposal method. Since this alternative contains multiple individual disposal units associated with a facility, the operations and closure of individual disposal units must be compatible with the site closure and stabilization plan.

This point has been considered and discussed in relation to shallow land burial by the NRC staff (Siefken and others, 1982), Tucker (1983), and Pangburn and Pennefill (1982). No conflicts or differences in design philosophy should occur between shallow land burial or belowground vault disposal. However, it is recommended that due consideration be given to the compatibility of the design, operation, and closure of individual units, as well as the overall site.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.51 (a)(3) states: "The disposal site must be designed to complement and improve, where appropriate, the ability of the disposal site's natural characteristics to assure that the performance objectives of Subpart C of this part will be met."

Discussion. This criterion is directly applicable to belowground vault disposal. In fact, the primary reason for considering any engineered facility for LLW disposal is that it may complement and improve the ability of the disposal site to meet the performance objectives.

Methods and features of a belowground vault which could be used to enhance the disposal site's natural characteristics have been discussed in section 2 of this report.

Recommendation. This criterion should be retained as is.

Criterion 10 CFR 61.51 (a)(4) states: "Covers must be designed to minimize to the extent practicable water infiltration, to direct percolating or surface water away from the disposed waste, and to resist degradation by surface geologic processes and biotic activity."

Discussion. This requirement is vital to satisfactory long-term performance of any near surface disposal facility. Again, methods and components which could be used to enhance cover performance have been discussed in section 2. For belowground vaults, the cover should be defined to include the vault roof. Therefore, the geochemical compatibility of site soils and construction materials should be assessed, as discussed in the section on additional technical considerations for site suitability, section 3.1.3.2.

Recommendation. The criterion should be retained as is. This recommendation is in agreement with the intent of the Task 1 report position. No modification is thought to be necessary to cover the need to assess geochemical compatibility of soil backfill and concrete or other construction materials or waste packages, as called for in the Task 1 report.

Criterion 10 CFR 61.51 (a)(5) states: "Surface features must direct surface water drainage away from disposal units at velocities and gradients which will not result in erosion that will require ongoing active maintenance in the future."

Discussion. The objective of this requirement is valid. Methods and features for enhancing surface drainage and minimizing erosion and resulting maintenance have been suggested in previous sections of this report. Tucker (1983) also recommends surface grading practices to minimize this problem. He also provides guidance on susceptibility of various soils to erosion and recommends various surface ditch profiles and slopes for reducing erosion of the drain soils.

The primary methods for minimizing erosion are to limit the area over which runoff flows, provide gentle slopes, and channel the runoff into drainage ditches which may be sodded or covered by concrete or other materials to protect them.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.51 (a)(6) states: "The disposal site must be designed to minimize to the extent practicable the contact of water with waste during storage, the contact of standing water with waste during disposal, and the contact of percolating or standing water with wastes after disposal."

Discussion. Again this requirement is valid and achievable. The risk of each of the potential cases of contact of water with wastes can be minimized. Temporary storage areas should be sloped and covered with roofs, or temporary storage times should be as short as possible. If drainage layers and gravity drainage are used, the contact of standing water with wastes during disposal should be minimal. Disposal operations should cease during rain and snow storms. If use of satisfactory backfill, surface sealants, and cover materials and construction methods are adhered to, the contact of infiltrating water should be minimized.

Recommendation. The criterion should be retained as is.

3.2.3 Suggested Additional Technical Considerations

The need to plan for individual disposal unit closure, as well as site closure, as discussed under 61.51 (a)(2) should be considered.

Also, as stated under 61.51 (a)(4), the need to ensure geochemical compatibility of soil backfill and construction materials should be considered.

3.3 Operations and Closure

3.3.1 Importance of Well-Planned and -Executed Operations and Closure Strategy

The main points to consider in planning for operations and closure of any LLW disposal facility are:

(1) Worker safety with respect to radiological hazards and hazards associated with excavation, construction, and maintenance of the site facilities.

(2) Compatibility of activities to minimize interference among construction, operations, monitoring, and temporary and final closure.

(3) Avoidance of activities that would lead to long term active maintenance problems.

(4) Records management and quality control and assurance.

(5) Maintenance of a buffer zone of sufficient lateral and vertical extent that enough space and time would be available to carry out remedial actions should they be required. The remedial action plan should be keyed to minimizing off-site releases of radionuclides during the period of significant hazard.

(6) Efficient land use.

3.3.2 Assessment of Existing Criteria

The 11 existing criteria for evaluation of land-disposal-facility operation and disposal-site closure are listed under 10 CFR Part 61 Subpart D, paragraph 61.52.

As was done in the previous sections for site suitability and design, each criterion is listed, discussed, and a recommendation is then made to retain the criterion as is, modify the criterion, or not apply it to the evaluation of this method. Additional technical considerations are discussed at the end of this section.

Criterion 10 CFR 61.52 (a)(1) states: "Wastes designated as Class A pursuant to paragraph 61.55, must be segregated from other wastes by placing in disposal units which are sufficiently separated from disposal units for the other waste classes so that any interaction between Class A wastes and other wastes will not result in the failure to meet the performance objectives in Subpart C of this Part. This segregation is not necessary for Class A wastes if they meet the stability requirements in paragraph 61.56(b) of this part."

Discussion. The rationale behind this requirement is that mixing of structurally unstable Class A wastes with Class B and Class C wastes could lead to differential settlement of the waste packages and the disposal unit cover. Significant differential settlement would, in turn, lead to cracking of the cover and significant infiltration into the disposal unit.

However, a belowground-vault disposal unit is a stable, self-supporting unit that, by itself, satisfies the stability requirements of 61.56 (b)(1). It does not rely on structural support from the waste packages. Deterioration of waste packages would not result in cover settlement.

As mentioned in the introduction of this report, waste segregation was not considered as a prerequisite to disposal in engineered facilities. However, a potential problem that could result from decomposition of unstable Class A wastes should be considered. Products of decomposition of unstable Class A wastes could include gases and liquids which could damage the vault structure through chemical attack. This potential problem and economic consideration are strong incentives to avoid disposal of unstable Class A wastes in disposal vaults. If unstable wastes are disposed of in vaults, the wastes must be shown to pose no threat to the vault materials.

Therefore, although segregation of unstable Class A wastes is judged to be unnecessary for avoidance of settlement and infiltration, other incentives exist to encourage segregation or stabilization, prior to disposal.

Recommendation. The criterion may be retained, although it is not directly applicable as written. For the reasons stated in the above discussion, segregation or stabilization of unstable Class A wastes is recommended.

Criterion 10 CFR 61.52 (a)(2) states: "Wastes designated as Class C pursuant to paragraph 61.55, must be disposed of so that the top of the waste is a minimum of 5 meters below the top surface of the cover or must be disposed of with intruder barriers that are designed to protect against an inadvertent intrusion for at least 500 years."

Discussion. Class C wastes represent the greatest long-term potential radiological hazard of any waste presently acceptable for near-surface disposal, primarily the hazard to the inadvertent intruder. Consequently, these wastes should be isolated from the inadvertent intruder by a greater distance or barrier. The requirement is valid and may be achievable by deeper disposal of Class C, by the use of durable, intruder resistant packaging, by disposing of Class C only in the bottom of disposal units or with Class B or stabilized Class A wastes stacked above and around the sides of Class C wastes. Significant intruder barriers such as concrete or metal covers used in vault construction could also serve as intruder barriers.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(3) states: "All wastes shall be disposed of in accordance with the requirements of paragraphs (a)(4) through (11) of this section."

Discussion. The referenced requirements are discussed individually below.

Recommendation. This umbrella criterion can be retained without impact for any disposal method.

Criterion 10 CFR 61.52 (a)(4) states: "Wastes must be emplaced in a manner that maintains the package integrity during emplacement, minimizes the void spaces between packages, and permits the void spaces to be filled."

Discussion. Maintenance of package integrity is important for any disposal method. Rupture of packages during operations would result in higher risks of radiation exposure to workers, and could result in contamination of equipment, areas adjacent to the disposal unit, and even offsite contamination if contaminated equipment leaves the site.

Minimization of voids promotes efficient use of disposal space. However, minimization of voids and filling of void spaces between waste packages in belowground vault disposal units has no effect on minimization of subsidence. Radionuclide pathway analyses may indicate that migration is impeded by filling voids and therefore, the filling of voids may be desirable.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(5) states: "Void spaces between waste packages must be filled with earth or other material to reduce future subsidence within the fill."

Discussion. See the discussion in 61.50 (a)(4) above. The objective of minimizing subsidence is not dependent on filling of voids. However, filling of voids may impede radionuclide migration and is therefore encouraged.

Recommendation. The criterion may be retained, but its objective is not applicable to belowground vault disposal. The potential benefits of void filling should be assessed.

Criterion 10 CFR 61.52 (a)(6) states: "Waste must be placed and covered in a manner that limits the radiation dose rate at the surface of the cover to levels that at a minimum will permit the licensee to comply with all provisions of paragraph 20.105 of this chapter at the time the license is transferred pursuant to paragraph 61.30 of this part."

Discussion. This criterion has a valid and achievable goal. If covers are defined to include the vault roof, then the criterion is judged to be applicable to belowground vault disposal. Additionally, during the "operational" period of each unit, radiation dosages must also be limited at the surface, and additional shielding should be provided over high-activity wastes during the interim between placement and closure. It should be noted that the waste package and structural features of the disposal unit, e.g., the walls and roof, would enhance shielding and reduce surface doses.

Class C wastes and wastes with high surface radiation should be placed on the bottom and center of the disposal unit and other wastes with lower surface radiation should be placed above and around the sides to reduce surface dose rates.

Recommendation. The criterion should be retained. However, temporary closure should be addressed, as recommended in the Task 1 report, either in the form of regulatory guidance or additional criteria. Modification of 61.52 (a)(6) may be appropriate for this purpose.

Criterion 10 CFR 61.52 (a)(7) states: "The boundaries and locations of each disposal unit (e.g., trenches) must be accurately located and mapped by means of a land survey. Near-surface disposal units must be marked in such a way that the boundaries of each unit can be easily defined. Three permanent survey marker control points, referenced to United States Geological Survey (USGS) or National Geodetic Survey (NGS) survey control stations, must be established on the site to facilitate surveys. The USGS or NGS control stations must provide horizontal and vertical controls as checked against USGS or NGS record files."

Discussion. This requirement is necessary to ensure positive location of disposal units in case remedial action becomes necessary and to reduce the likelihood of inadvertent intrusion. These goals are desirable and technically achievable, using standard surveying methods.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(8) states: "A buffer zone of land must be maintained between any buried waste and the disposal site boundary and beneath the disposed waste. The buffer zone shall be of adequate dimensions to carry out environmental monitoring activities specified in paragraph 61.53(d) of this part and take mitigative measures if needed."

Discussion. This requirement was specified to ensure that adequate space and time would be available to detect and correct any performance deficiencies, i.e., radionuclide migration, before the deficiences manifest themselves at the site boundary. A fixed distance was not specified because of the variable relationship between radionuclide and ground-water travel times and site soil characteristics, primarily hydraulic conductivity and adsorption capacity. An additional consideration is to ensure that sufficient space exists between and around disposal units to carry out normal operations and closure activities. This is a practical requirement that can be easily implemented.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(9) states: "Closure and stabilization measures as set forth in the approved site closure plan must be carried out as each disposal unit (e.g., each trench) is filled and covered."

Discussion. As discussed by Pangburn and Pennifill (1982), the purpose of this requirement is primarily to minimize the number and extent of activities to be performed at the time of site closure. By closing and stabilizing disposal units as they are completed, the operator will be able to focus on final closure and stabilization. Moreover, early closure and stabilization will help to minimize infiltration, lower dose rates to site personnel and protect waste package integrity. Early closure of filled disposal units also provides valuable experience from which to fine-tune final closure methods. Finally, if completed disposal units are not promptly closed and stabilized, the probability of achieving long-term isolation and avoidance of the need for continuing active maintenance could be compromised. Therefore, an applicant should provide, as part of the application, a closure and stabilization plan to be implemented upon completion of any given disposal unit. To assure closures within a reasonable time period, a construction sequencing plan with projected future waste quantities and categories should be submitted to indicate facility operation and closure time periods.

Disposal units that have been closed should be periodically inspected to ensure satisfactory performance. Such inspections should identify areas of erosion, cover cracking and settlement, ponding, and condition and extent of vegetation. Areas of lush vegetation should be checked to determine if these areas are wetter than adjacent areas.

Problems noted should be accompanied by plans for remedial actions. Subsequent inspections should note whether such remedial actions were undertaken and whether the noted problem has been corrected or still exists. Procedures similar to these have been followed for decades by the Corps of Engineers in their periodic inspections and evaluations of locks and dams and other civil works.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(10) states: "Active waste disposal operations must not have an adverse effect on completed closure and stabilization measures."

Discussion. This requirement seeks to ensure that active operations do not result in damage to completed disposal units. Satisfaction of this requirement is achievable through planning of both normal operations and contingencies. Simple examples would include allowing enough room between disposal units for temporary storage of excavated materials and normal equipment movement such that adjacent units and monitoring points are not endangered.

Sufficient room should be provided between arrays of disposal units to allow for surface water management features and closure of completed units.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.52 (a)(11) states: "Only wastes containing or contaminated with radioactive materials shall be disposed of at the disposal site."

Discussion. This criterion is directly applicable to the belowground vault disposal alternative. However, it may not go far enough in stating what may not be disposed of, e.g., hazardous or toxic wastes that are slightly radioactive. This issue is considered within the criteria for waste characteristics, 10 CFR paragraph 61.56. However, the intent of paragraph 61.56 is to facilitate handling and to ensure protection of the health and safety of workers and to protect the environment from incidental concentrations of hazardous material. In addition, the potential for damage to the engineered disposal unit from the contained wastes, e.g. chemical attack, should be considered.

Recommendation. The criterion should be retained as is, but the additional concern discussed above should be addressed.

3.3.3 Suggested Additional Technical Considerations

In addition to the comments and suggestions made in the discussion of each existing criterion, it is recommended that the potential benefits of filling void spaces within the vaults be assessed, as well as the potential for increased worker exposures.

3.4 Monitoring

3.4.1 Objectives of Monitoring

The overall objective of monitoring any low-level radioactive waste disposal facility is to provide reasonable assurance that the performance objectives are being met. Monitoring is considered to include the systematic collection, analysis, and interpretation of data related to the radiological, chemical, physical, and environmental properties of specific media in the vicinity of a LLW site during all phases of site life. Monitoring should include measurements and observations of structural performance.

In addition to determining compliance with the performance objectives established in 10 CFR Part 61, the monitoring program should also:

a. Aid in site characterization.

b. Establish a statistical data base for background values of parameters of concern.

c. Provide a data base useful in the selection and verification of a site model.

d. Provide a method for determining when corrective actions are necessary, i.e., a plan of action to be implemented when the values of one or more parameters exceed a specified action level.

The monitoring program extends from the preoperational site investigation program through the operation period, and for some time after closure.

Lutton and others (1982a, 1982b, and 1983) in a series of three reports (NUREG/ CR-2700, NUREG/CR-3038, and NUREG/CR-3164) described the parameters which should be monitored, test methods and equipment required to measure these parameter values, and a comprehensive subsurface monitoring program that could achieve the intended objectives at LLW disposal sites. Sedlett and others (1982) have also developed a handbook for environmental monitoring of LLW disposal sites. Rogers, Sutherland, and Adam (1982) have developed a handbook for LLW disposal that discusses specific objectives and gives examples of monitoring techniques suitable for shallow land burial. Most of these recommendations would be equally applicable to a belowground vault disposal facility.

It is not the purpose of this report to make recommendations concerning a specific program for monitoring disposal facilities. Such a program must be site specific and based on the design and plans for operation and closure of the facility. The above references, NRC staff position papers, and the existing monitoring criteria, along with the recommendations in this report, should provide adequate basis for development of specific monitoring programs.

It should be noted that, if the disposal facility is properly sited, designed, and operated, the major function of the monitoring program is to provide reassurance of satisfactory performance and safety of the facility.

3.4.2 Assessment of Existing Criteria

The existing criteria for environmental monitoring of land disposal of LLW are contained in paragraph 61.53 of 10 CFR Part 61 Subpart D. These four criteria are listed in subparagraphs 61.53(a)-(d) and are listed and discussed individually below. Additional technical considerations are discussed at the end of this section.

Criterion 10 CFR 61.53 (a) states: "At the time a license application is submitted, the applicant shall have conducted a preoperational monitoring program to provide basic environmental data on the disposal site characteristics. The applicant shall obtain information about the ecology, meteorology, climate, hydrology, geology, geochemistry, and seismology of the disposal site. For those characteristics that are subject to seasonal variation, data must cover at least a twelve month period."

Discussion. This requirement is basic to the establishment of site suitability, design-basis natural events, and operations and closure plans. While the specific information that is to be collected and its relative importance can be expected to vary, as well as the use to which it is put, the need for a systematic program is absolute.

Recommendation. This criterion should be retained as is.

Criterion 10 CFR 61.53 (b) states: "The licensee must have plans for taking corrective measures if migration of radionuclides would indicate that the performance objectives of Subpart C may not be met."

Discussion. This requirement is valid and suggests the need for further requirement that the licensee have on file plans for specific actions if detected concentrations or rates of radionuclide migration exceed preestablished limits. The action plan should indicate methods and equipment to be used and the time table for mobilization. This requirement is keyed to the requirement for and size of the buffer zone, so that reaction and implementation of the planned action can be effected before radionuclides migrate beyond the site boundary.

Recommendation. The criterion should be retained as is.

Criterion 10 CFR 61.53 (c) states: "During the land disposal facility site construction and operation, the licensee shall maintain a monitoring program. Measurements and observations must be made and recorded to provide data to evaluate the potential health and environmental impacts during both the construction and the operation of the facility and to enable the evaluation of long-term effects and the need for mitigative measures. The monitoring system must be capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary."

Discussion. The criterion is valid. It is recommended, however, that at the time of license application and review, specific reporting requirements be included. The reporting requirements should be keyed to the specific sample data and frequency of measurements of those data that would be required by analyses to demonstrate satisfactory performance.

In addition, a plan should be submitted for disposal of surface drainage water and ground water that has been sampled, tested, and found to contain significant radionuclide concentrations. As discussed under the previous criterion, plans for mitigative measures should also be submitted for approval, prior to operation.

Recommendation. The criterion should be retained. However, it should be expanded to include the above requirements. Alternatively, these requirements should be incorporated in supplemental criteria.

Criterion 10 CFR 61.53 (d) states: "After the disposal site is closed, the licensee responsible for postoperational surveillance of the disposal site shall maintain a monitoring system based on the operating history and the closure and stabilization of the disposal site. The monitoring system must be capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary."

Discussion. The objective of this requirement is to ensure that the site continues to perform satisfactorily after closure and to provide a basis for checking on any previous problem areas, while allowing sufficient time to fix any observed deficiencies. This is a valid requirement.

Recommendation. The criterion should be retained as is.

3.4.3 Suggested Additional Technical Requirements

In addition to an approved monitoring program and plans for mitigative measures, it is recommended that the licensee be required to provide a disposal plan for water and other materials that have been sampled and tested.

It is further recommended that each disposal unit be monitored individually so that any problems that develop can be quickly traced to their origins and corrected.

4. CONCLUSIONS AND RECOMMENDATIONS

Belowground vaults have not been used for disposal of LLW. The US Department of Energy has used belowground vaults for storage of transuranic wastes at Oak Ridge National Laboratory. In Canada, belowground vaults and bunkers have been used for storage of LLW at Whiteshell and Chalk River. These facilities have all been designed to accommodate retrieval of wastes for final disposal later. Retrievability is not a requirement for alternative disposal methods or for current disposal methods. Consequently, the experience with storage is not entirely compatible with disposal nor of sufficient duration to reliably predict long-term performance of belowground vault disposal facilities. Reliable predictions are further complicated because of the lack of documented evidence on long-term durability of construction materials that might be used in vault construction. Extrapolation of short-term experience, augmented by theoretical analyses, short-term testing of engineered materials and components, and engineering judgement are all that can be used to predict long-term performance for belowground vaults.

However, a belowground vault does not rely as heavily on design features as an aboveground facility. The soil surrounding the vault provides waste isolation capabilities just as it does with shallow land burial. Therefore, a properly designed belowground vault may be expected to provide long-term waste isolation capabilities at least equal to shallow land burial. However, long-term predictions of performance may not be as reliable as one might wish.

In practice, several design features of belowground vaults may improve their performance. For example, the self-supporting structure reduces the potential for settlement or subsidence of the cover. Stability of waste packages, minimization of voids, and filling of voids are not critical to the prevention of subsidence. The structure also serves as an effective barrier to inadvertent intruders, plants, and burrowing animals. The potential for damage from erosion or other surface geological processes should be reduced, because of the structure's integrity. Infiltration rates may be reduced by the roof and wall barrier and the low-permeability cover. Free-draining backfill placed around the vault promotes drainage of any infiltrating water away from the vault, thus reducing the likelihood of contact of water with the waste packages.

Some disadvantages also may be expected with belowground vault disposal. For example, exposure of workers to radiation hazards may be higher unless remote handling is used. Access may be hampered and closure of filled vaults will be more complicated and require attention to details. Internal drains can be provided to remove moisture and these drains can be monitored. However, the drains may become a maintenance problem.

Except as discussed in the following paragraphs, all the existing criteria were found to be applicable to belowground vault disposal of LLW. In the assessment of existing site suitability criteria, all were found to be applicable to the disposal method. It was pointed out that engineered facilities can be designed to resist seismic risks, but the risk must be quantified as a design basis natural event.

For design, the requirement stated in 61.51 (a)(3) that the design features should complement and improve where appropriate the site's natural characteristics was emphasized. Indeed, this requirement is the primary reason to consider any engineered facility. The term "covers" used in 61.51 (a)(4) should be defined to include the vault roof. Geochemical compatibility of site soils and vault construction materials should be assessed to promote long-term integrity of the vault.

The objective of the requirement for segregation of wastes stated in 61.52 (a)(1) is to reduce the potential for subsidence and cracking of the cover that may occur as a result of decomposition and settlement of unstable wastes. Cover subsidence may lead to increased infiltration and contact of water with waste packages. However, the vault structure does not rely on the waste packages for structural support, and settlement of waste packages would not result in cover subsidence or increased infiltration. The objective of the criterion can be met without waste segregation. However, segregation or stabilization prior to disposal may be advantageous for other reasons. For example, products of decomposition of unstable Class A wastes might damage the vault construction materials through chemical attack. This potential problem and economic considerations are incentives to avoid disposal of unstable Class A wastes in belowground vaults.

Criterion 61.52 (a)(4) requires that wastes must be emplaced in a manner that maintains package integrity during emplacement, minimizes void spaces between packages, and permits voids to be filled. Criterion 61.52 (a)(5) requires that these voids must be filled with earth or other solid material to reduce future subsidence within the fill. Package integrity should be maintained to reduce worker exposures. However, minimization of void spaces between packages and filling of these voids has no effect on minimization of subsidence for this alternative. Subsidence may be minimized through proper compaction of the backfill and cover above the vault. However, radionuclide pathway analyses may indicate that migration is impeded by filling voids, in which case void filling may be desirable. Therefore, the potential benefits of void filling should be assessed.

In the assessment of 61.52 (a)(11), it was recommended that the potential for damage to the engineered disposal facility from the contained wastes, e.g. chemical attack, should be considered.

All of the monitoring criteria were found to be directly applicable to belowground vault disposal. Specific reporting requirements and a detailed plan of action are recommended, including plans for disposal of sampled soil, water and other materials that are shown to be contaminated.

Additional technical considerations that should be addressed in the evaluation of belowground vault disposal include:

> In the determination of site suitability, the occurrence and potential impacts of dispersive soils, expansive soils, liquefiable soils, corrosive soils, and areas undergoing land subsidence or solution-cavity formation should be assessed.

The chemical compatibility of construction materials, site soils, and waste form should be considered.

Temporary closure and individual disposal unit closure should be addressed, in addition to overall site closure, through submittal of a detailed plan for operations and closure of the facility. This plan should address disposal of soil, water, and other sampled materials found to be contaminated by radioactivity.

An issue not fully addressed by this study that deserves further investigation is long-term durability and performance of concrete and other construction materials. Appendix A represents a step in this direction for concrete, in that the major factors that impair long-term durability are identified and design and construction practices to minimize their impacts are recommended. The authors are aware of other limited research in this area but recommend that this area of research be emphasized and expanded. Materials research has significant potential payoffs not only for engineered disposal facilities, but also for waste packaging, transport, and storage, prior to disposal.

Although beyond the scope of this study, the possible advantages of matching waste classes and forms to the various disposal methods should be addressed. Tangible economic and performance benefits may be possible. Continued support of research in the area of improved waste packages and sorbent barriers is also recommended.

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GLOSSARY

ACTIVE MAINTENANCE: Any significant remedial activity needed during the period of institutional control to maintain a reasonable assurance that the performance objectives in 10 CFR 61.41 and 61.42 are met. Such active maintenance includes ongoing activities such as the pumping and treatment of water from a disposal unit or one-time measures such as replacement of a disposal unit cover. Active maintenance does not include custodial activities such as repair of fencing, repair or replacement of monitoring equipment, revegetation, minor additions to soil cover, minor repair of disposal unit covers, and general disposal site upkeep such as mowing grass.

ACTIVITY: A measure of the rate at which a material is emitting nuclear radiations; usually given in terms of the number of nuclear disintegrations occurring in a given quantity of material over a unit of time; the standard unit of activity is the curie (Ci), which is equal to 3.7×10^{10} disintegrations per second.

AGREEMENT STATES: Any States with which the Commission or the AEC has entered into an effective agreement under subsection 274b of the Atomic Energy Act of 1954. A Nonagreement State is any other State. (10 CFR 150.3)

AQUICLUDE: A formation which, although porous and capable of absorbing water, does not transmit it at rates sufficient to furnish an appreciable supply for a well or spring. (ASTM STP 746)

AQUIFER: Geologic stratum or set of beds with relatively high transmissivity and carrying ground water in quantities to make exploitation for consumption economically feasible.

BACKGROUND RADIATION: Radiation in the environment from naturally occurring radioactive elements, cosmic radiation, and fallout from man's activities such as nuclear weapons testing.

BUFFER ZONE: A portion of the disposal site that is controlled by the licensee and that lies under the disposal units and between the disposal units and the boundary of the site.

CURIE (Ci): A unit of radioactivity defined as the amount of a radioactive material that has an activity of 3.7×10^{10} disintegrations per second (d/s); millicurie (mCi) = 10^{-3} curie; microcurie (Ci) = 10^{-6} curie; nanocurie (nCi) = 10^{-9} curie; picocurie (pCi) = 10^{-12} curie; femtocurie (fCi) = 10^{-15} curie.

DECONTAMINATION: The selective removal of radioactive material from a surface or from within another material.

DISPOSAL SITE: That portion of a land disposal facility which is used for disposal of waste. It consists of disposal units and a buffer zone.

DISPOSAL UNIT: A discrete portion of the disposal site into which waste is placed for disposal. For current near-surface disposal the unit is usually a trench.

ENGINEERED BARRIER: A man-made structure or device that is intended to improve a land disposal facility's ability to meet the performance objectives in 10 CFR Part 61, Subpart C.

ENGINEERED DISPOSAL: As used in this report, the disposal of radioactive wastes, usually in suitable sealed containers, in any of a variety of structures especially designed to protect them from water and weather and to prevent leakage to the biosphere by accident or sabotage.

ENVIRONMENTAL SURVEILLANCE: Monitoring of the impact on the surrounding region of the discharges from industrial operations, forest fires, storm runoff, or other natural or man-induced events.

EXPOSURE: A measure of the ionization produced in air by X or gamma radiation. It is the quotient of (1) the sum of the electrical charges on all ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by (2) the mass of the air in the volume element. The special unit of exposure is the Roentgen. (Radiological Health Handbook, U. S. Dept. of HEW). Acute exposure generally refers to a high level of exposure of short duration; chronic exposure is lower-level exposure of long duration.

GROUND WATER: Water that exists or flows below the ground surface (within the zone of saturation).

GROUT: Fluid or semifluid material, often containing Portland cement, which may be pumped or poured into earth strata and by setting up into a solid state, provides mechanical stabilization or water flow control.

HALF-LIFE: The time in which half the atoms of a particular radioactive substance disintegrate to another nuclear form. Measured half-lives vary from millionths of a second to billons of years. After a period of time equal to 10 half-lives, the radioactivity of a radionuclide has decreased to 0.1 percent of its original level.

HAZARDOUS WASTE: Those wastes designated as hazardous by Environmental Protection Agency regulations in 40 CFR Part 261.

HYDROGEOLOGY: The study of ground water, with particular emphasis on its chemistry, mode of migration, and relation to the geologic environment. (Davis and De Wiest, 1966).

HYDROGEOLOGIC UNIT: Any soil or rock unit or zone which by virtue of its porosity or permeability, or lack thereof, has a distinct influence on the storage or movement of ground water.

IN SITU: In the natural or original position; used to refer to inplace experiments at a storage or disposal site.

INADVERTENT INTRUDER: A person who might occupy a disposal site after closure and engage in normal activities, such as agriculture, dwelling construction, or other pursuits, in which the person might be unknowingly exposed to radiation from the waste.

INTRUDER BARRIER: A sufficient containment of the waste that inhibits human contact with waste and helps to ensure that radiation exposures to an inadvertent intruder will meet the performance objectives set forth in 10 CFR 61; or engineered structures that provide equivalent protection to the inadvertent intruder.

ION: Atomic particle, atom, or chemical radical bearing an electrical charge, either negative or positive.

ION EXCHANGE: A reversible interchange that takes place between ions of like charge, usually between ions present on an insoluble solid and ions in a solution surrounding the solid. An important process in both fundamental and industrial chemistry.

ION-EXCHANGE RESIN: An insoluble polymerized electrolyte that contains either acidic groups for exchanging cations or basic groups for exchanging anions. It contains large, high-molecular-weight ions of one charge and small, simple ions of the opposite charge. The small ions undergo exchange with ions in solution.

IONIZING RADIATION: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

ISOTOPES: Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number. Identical chemical properties exist between isotopes of a particular element.

KARST: Surface or subsurface rock mass conditions characterized by solution-formed caverns, cavities, open joints, pinnacles, and depressions of a highly irregular form. Almost exclusively applied to carbonate lithologies, e.g., limestone.

LAND DISPOSAL FACILITY: Land, buildings, and equipment intended to be used for the disposal of radioactive wastes into the subsurface of the land. A geologic repository as defined in 10 CFR 60 is not considered a land disposal facility. (10 CFR 61.2)

LEACHING: The process of extracting a soluble component from a solid by the percolation of a solvent (e.g., water) through the solid.

LIQUEFIABLE: Susceptible to near-total loss of shear strength and bearing capacity duing seismic disturbances; used with reference to soils.

LITHOLOGY: The character of a rock formation or of the rock found in a geological area or stratum expressed in terms of its structure, mineral composition, color, and texture.

LOW-LEVEL RADIOACTIVE WASTE (LLW): Radioactive waste not classified as high-level radioactive waste, transuranic waste, spent nuclear fuel, or by-product material as defined in section 11e. (2) of the Atomic Energy Act of 1954. (P.L. 96-573) Radioactive wastes containing source, special nuclear, or by-product material that are acceptable for disposal in a land disposal facility (10 CFR 61.2) For explanation of Class A, Class B, and Class C LLW, see 10 CFR 61.55 and 61.56.

NEAR-SURFACE DISPOSAL FACILITY: A land disposal facility in which radioactive waste is disposed of in or within the upper 30 meters of the earth's surface.

PERMEABILITY: The capacity of a porous medium to conduct liquids or gases.

PIEZOMETER: An instrument for measuring pressure head in ground water. In an unconfined aquifer with a free water table a piezometer is frequently an open-bottomed monitor well extending below that water table.

PSYCHROMETER: Device used for measuring the amount of water vapor in air; e.g., a hygrometer.

PYROPHORIC: Igniting spontaneously. A pyrophoric liquid is any liquid that ignites spontaneously in dry or moist air at or below 130°F (54.5°C). A pyrophoric solid is any solid material, other than one classed as an explosive, which under normal conditions is liable to cause fires through friction, retained heat from manufacturing or processing, or which can be ignited readily and when ignited burns so vigorously and persistently as to create a serious transportation, handling, or disposal hazard. Included are spontaneously combustible and water-reactive materials.

RAD: The unit of absorbed dose equal to 100 ergs per gram or 0.01 joule per kilogram.

RADIOACTIVITY: The property of certain nuclides of spontaneously emitting particles or gamma radiation, or of emitting X radiation following orbital electron capture, or of undergoing spontaneous fission. (Radiological Health Handbook, U. S. Dept. of HEW)

REM: A special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors. (Radiological Health Handbook, U. S. Dept. of HEW) The dosage of any ionizing radiation that will cause the same amount of biological injury to human tissue as one roentgen of X-ray or gamma-ray dosage. (Webster's Third New International Dictionary) (1 millirem = 0.001 REM)

REPOSITORY: A term generally applied to a facility for the disposal of radioactive wastes, particularly high-level waste and spent fuel.

ROENTGEN: The special unit of exposure. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air. (Radiological Health Handbook, U. S. Dept. of HEW) The international unit of X radiation or gamma radiation that is the amount of radiation producing, under ideal conditions in one cubic centimeter of air at 0°C and 760 mm Hg pressure, ionization of either sign equal to one electrostatic unit of charge. (Webster's Third New International Dictionary)

SEISMIC: Of, pertaining to, of the nature of, subject to, or caused by an earthquake.

SITE CLOSURE AND STABILIZATION: Those actions that are taken upon completion of operations that prepare the disposal site for custodial care and that assure that the disposal site will remain stable and will not need ongoing active maintenance.

SUBSIDENCE: Sinking or depression of the ground surface; generally due to loss of subsurface support.

SURVEILLANCE: Observation of the disposal site for purposes of visual detection of need for maintenance, custodial care, evidence of intrusion, and compliance with other license and regulatory requirements.

TECTONIC: Of or relating to the deformation of the earth's crust, the forces involved in or producing such deformation, and the resulting rock structures and external forms.

TRANSMISSIVITY: A property of an aquifer; the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

TRANSURANIC (TRU) WASTE: Waste that without regard to source or form, at the end of institutional control periods is contaminated with alpha-emitting radionuclides of atomic number greater than 92 and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram (nCi/g), or has a smearable alpha contamination greater than 4000 dpm/cm^2 averaged over the accessible surface.

UNSATURATED ZONE: The zone of soil or rock between the ground surface and the water table; also termed the vadose zone.

VAULT: An artificial enclosed space covered by an overhead structure; especially a passage or room used for storage or safekeeping.

VULCANISM: The processes by which magma (molten rock material within the earth) and its associated gases rise into the earth's crust and are extruded onto the earth's surface and into the atmosphere.

WATER TABLE: The surface within an unconfined aquifer between the zone of saturation and the zone of aeration; that surface of a body of unconfined ground water at which the pressure is equal to atmospheric pressure.

APPENDIX A

Long Term Performance and Durability of Portland Cement Concrete as the Building Material for Engineered Facilities

by R. H. Denson
CTD/SL

Contents

List of Tables

1. Introduction

The disposal of low-level radioactive waste in engineered facilities requires an in-depth evaluation of the construction materials used to attempt the prediction of the service life of structures used for this disposal. This section of the report addresses the parameters to be considered in the use of reinforced portland-cement concrete as the building material for disposal vault or other engineered facilities.

Predicting behavior and durability of materials and structures for long periods of time, such as 500 years, has, as its foundation, extrapolation of short-term data, which in many cases may lack a proper rationale. The ancient Roman engineers and builders produced constructions that we can examine today but passed on very little written narrative of how they designed and constructed their projects (Malinowski, 1979). Present-day efforts to reconstruct, by deduction, the formulation of concrete mixtures, the identification of the exact materials, and a definite statement as to construction methodology have met with only slight success (Malinowski, 1979 and Roy and Langton, 1983). However, these studies permit better understanding of the aging process that may be expected for certain materials.

Predicting the long-term stability and performance of materials such as cements, mortars, and concrete may be approached in two ways: (1) examination of the physical performance of old structures and (2) interpretation of the chemical activity of the observed durability of old cementing materials.

Long-term performance is an approximate synonym of durability, and the factors which impair such durability will determine its long-term performance.

Generally, concrete durability depends on its porosity, permeability, absorptivity, capillarity, response to imposed stresses, and bond of the components.

2. Factors that Impair the Integrity of Concrete

The structural integrity of a reinforced portland-cement concrete XQwchQcwn KX e YcohQKro rf the quality and durability of the structure in wnXyroXn Qr Qdn eyyWKna WreaX eoa XQwnXXnX eoa rY Qdn acwepKWKQg eoa zceWKQg rY Qdn hrohwnQn hroQeKona Ko Qdn XQwchQcwn% /cwepKWKQg rY e XQwchQcwn deX pnno anYKona "?_A|& ®866® eX DQdn XeYn ynwYrwieohn rY e XQwchQcwn rw e yrwQKro oY e XQwchQcwn Yrw Qdn anXKvona WKYn nkynhQeohg%D /cwepKWKQg rY yrwQWeoa cement concrete has been defined (ACI, 1977) as "its ability to resist weathering action, chemical attack, abrasion, or any other process of deterioration." It is essential to recognize the main types of concrete deterioration and then address measures and techniques that can be employed to protect against these attacks.

American Concrete Institute (ACI) Committee 201 (ACI, 1977) has listed five important causes of concrete deterioration as: (1) freezing and thawing, (2) aggressive chemical exposure, (3) abrasion, (4) corrosion of steel and other metals embedded in concrete, and (5) chemical reactions of aggregates. The following paragraphs define and discuss these causes.

2.1 Freezing and Thawing

Freezing and thawing damage is the phenomenon that occurs when critically saturated concrete is subjected to freezing and thawing. Hardened cement paste and aggregate have very different behavior responses to freezing and thawing and therefore should be considered separately.

2.1.1 Freezing and thawing of cement paste. The porosity of cement paste, in fairly dense and well consolidated concrete, is between 30 percent and 50 percent. This pore structure becomes reservoirs for water which can freeze and cause disruptive and damaging action. The research done by Powers (1945, 1954, 1955), Helmuth (1960), Collins (1944), and Litvan (1974) produced what is generally accepted as the mechanisms taking place during freezing, though each researcher's findings differ somewhat in detail. It is now believed by many researchers that osmotic pressure of the freezing water in the pores and connecting capillaries causes most of the frost damage in cement paste (ASTM, 1977). The pressures generated by this mechanism cause the paste to fail, which in turn, causes the concrete mass to fail.

Generally, it is agreed (and has been demonstrated time and again) that air entrainment of cement paste can produce a paste that will not be affected by freezing and thawing provided sufficient hydration of cement has taken place before the paste is allowed to freeze while critically saturated. Air entrainment produces a pore distribution system, with appropriate distances between pores, which will accommodate ice movement and pressures.

2.1.2 Freezing and thawing of aggregate particles. As just stated, air entrainment can prevent damage in cement paste, but the freezing action in aggregate particles must also be considered so as to produce a concrete that will be free of damage.

The basic mechanism is called "the hydraulic pressure theory (ASTM, 1977)." Powers (1945) found that the pores of rocks, which are often larger than paste pores, if water filled, expel water during freezing and thereby produce a hydraulic pressure which can cause failure.

In addition, Verbeck and Landgren (1960) found that in coarse aggregate from any given natural rock, there is a critical size below which, if unconfined by cement paste, the material can be frozen without damage.

The overall effect on a concrete composed of sound aggregate and paste of appropriate maturity which has an appropriate air-entrained void system characterized by a spacing factor (maximum distance from any point in the paste to the periphery of a nearby air void) of less than 0.008 in. is one in which no destructive stresses are produced during freezing.

2.2 Aggressive Chemical Exposure

Concrete of good quality will perform satisfactorily when exposed to many chemicals. There are, however, some chemical environments under which the useful life of concrete will be short.

Table 1 lists certain chemicals which attack concrete and recommendations for preventative or remedial protection (Highway Research Board of the National Academy of Sciences, 1966).

Chemical attack on concrete is generally the result of exposure to sulfates or acids, and these are discussed below.

Sulfate attack is a particular problem in arid areas, such as the northern Great Plains area and parts of the western United States. Sulfates such as those found in soils and groundwaters near concrete structures can attack concrete. In the presence of moisture, an expansive reaction takes place between the tricalcium aluminate (C_3A) phase of portland cement and sulfates to produce calcium sulphoaluminate which will cause disruption of concretes. If the C_3A content is lowered during burning of the cement clinker by converting it to tetracalcium alluminoferrite (C_4AF), which is not so suceptible, this produces an effective means of combating sulfate attack.

Type V cement which may not contain more than 5 percent by weight of C_3A, has been found to perform satisfactorily in severe sulfate exposures. Type II cement may not contain more than 8 percent by weight of C_3A and provides moderate sulfate resistance.

In general, portland cement is not acid resistant, but it can withstand weak acids (pH greater than 4.0). Water draining from mines or landfills, some industrial water, and falling rain may contain or form acids which attack concrete. Also, sulfuric acid, carbonic acid, and sulfates are common in ground-water, which could cause corrosion of embedded steel and sulfate attack in concrete.

Acid attack, with the attendent resulting deterioration, is characterized by a chemical reaction between the acid and the calcium hydroxide of the hydrated portland cement. This results in the formation of water-soluble calcium compounds. These in turn are leached away. This total mechanism destroys the binding ability of the cement paste.

Table 1

Certain Chemicals Harmful to Concrete (Effects and Remedies)

Substance	Effect	Remedy
Acetic acid	Causes slow disintegration	Use heavy duty floors with bituminous or polysulfide coatings
Calcium sulfate	Because of limited solubility, attack is less than other sulfates	Use epoxy, rubber, or bituminous coatings: use high quality concrete with high cement factor and air entrainment
Carbon dioxide	No damage to mature concrete, but can dissolve in water to form carbonic acid	Use surface hardeners and coatings: properly vent combustion heaters when placing concrete in heated enclosure
Carbonic acid	Very corrosive to lean mixtures; slowly disintegrates better quality concrete	Use dense, impermeable concrete with high cement factor: use epoxy, neoprene, or vinyl coatings
Fats and oils	Attack varies, depending on concentration of fatty acids and viscosity of oils	Use low water-cement ratio; dense, impermeable concrete; use surface hardeners (Magnesium or zinc flurosilicate), oil-insoluble resin
Hydrobromic acid, hydrochloric acid	Constant contact by strong solution destroys concrete; weak solutions attack slowly	Use protective coatings per ACI 515
Hydrogen sulfide	Sulfuric acid is produced in moist, oxidizing environments, which causes slow disintegration	Use concrete of low permeability; use coatings of polyester, neoprene or epoxy
Iron sulfide	Slow disintegration of low quality concrete if substance contains ferric sulfate	Use good quality concrete; use epoxy, chlorosulfonated polyethylene, or polyester coatings

Table 1 (Continued)

Substance	Effect	Remedy
Magnesium sulfate	0.5% solution (or more) aggressively attacks concrete with low sulfate resistance, causes disruptive expansion	Use high quality air-entrained concrete with high cement factor; use epoxy, rubber, or bituminous coatings
Nitric acid	Constant contact of strong solution destroys concrete	Use protective coatings per ACI 515
Sodium carbonate in solution	Does not affect mature concrete but causes fresh concrete to deteriorate	Protect fresh concrete from contamination
Sodium chloride	Corrodes reinforcing steel which can damage concrete member	Avoid use or presence of substance
Sodium sulfate	0.5% solutions (and greater) strongly attacks concrete of inadequate sulfate resistance	Use high quality air-entrained concrete with high cement factor; use bituminous, rubber, or epoxy coatings
Sulfur dioxide	Dry gas combined with moisture from acids cause long-term deterioration	Use vinyl, epoxy, or chlorinated rubber coatings
Sulfuric and sulfurous acids	Constant contact with strong solutions destroys concrete	Use protective coatings per ACI 515

2.3 Abrasion

Abrasion is the wearing away of a concrete surface by rubbing and friction (ACI, 1967). To consider several mechanisms of abrasion, Prior (1966) has recommended four classifications of abrasion:

(1) Wear on concrete floors (foot traffic, light trucking, skidding, scraping, or sliding of objects on the surface).

(2) Wear on concrete roadways (automobiles with studded tires or chains, heavy trucks).

(3) Erosion in hydraulic structures (waterborne abrasive materials).

(4) Wear on water-carrying systems composed of concrete (high velocities and negative pressures).

Abrasion is a physical wearing away or breaking off of material on the surface of the concrete by the abrading agent. The factors, therefore, which affect the abrasion resistance of concrete to a given abrading agent are: compressive strength, aggregate properties, finishing methods, use of toppings or coatings, and curing. Therefore, higher compressive strength results in greater abrasion resistance; harder coarse and fine aggregate results in higher resistance; properly timing the finishing operations and producing a smooth, dense surface gives higher resistance; application of metallic or nonmetallic coatings to toughen the surface gives higher resistance; and, use of proper curing agents for the required time gives a higher resistance.

2.4 Reactive Aggregates

No aggregates should be considered completely chemically inert. Some of the chemical reactions can be beneficial but others can cause disruptive damage such as abnormal expansion, cracking, and loss of strength (Woods, 1968).

The most predominant harmful reaction is "alkali-silica reaction" and is defined as the reaction between hydroxyl ions associated with the dissolution of the cement alkalies (Na_2O and K_2O) and certain siliceous constituents that may be present in aggregates. This disruption is characterized by expansion and severe cracking of the concrete structure.

Another form of reaction is that between the hydroxyl ions associated with dissolution of the cement alkalies and certain carbonate rocks, usually argillaceous dolomitic limestones. The disruptive damage is usually characterized by expansion, cracking, and aggregate degradation.

Other types of chemical reaction include oxidation or hydration of certain unstable mineral oxides, sulfates, or sulfides that occur after the aggregate has been incorporated into the concrete (Highway Research Board of the National Academy of Sciences, 1966).

All of these reactions usually result in such disruptive damage that the deteriorated concrete must be removed and replaced by sound concrete of better quality.

Table 2 is a summary of the deleterious aggregates discussed herein, derived from ASTM (1977).

2.5 Corrosion of Embedded Material

For corrosion of steel embedded in concrete to occur, the following conditions must all be met: (1) the provision of an anode and cathode, (2) the maintenance of an electrical circuit, (3) the presence of moisture, and (4) the presence of oxygen (Mindness and Young, 1981). Under most conditions, good quality concrete provides adequate protection of embedded steel against corrosion. This is due to the high alkalinity of the concrete (pH of about 12 to 12.5) which causes a passive oxide film that prevents corrosion to form on the surface of the steel. The degree to which concrete will provide satisfactory protection is in most instances a function of the quality of the concrete, the depth of concrete cover, and the degree to which good practices are followed throughout the entire construction operation (ACI, 1979).

The quality characteristic of concrete includes low permeability and proper mixture proportions. The permeability of concrete is a major factor affecting the process of corrosion of embedded materials. Low water-cement ratio with well-graded coarse and fine aggregates produce less permeable concrete and thus provide greater assurance against corrosion. Water-cement ratios should not exceed 0.40 for concrete exposed to sea or brackish water, or in contact with more than moderate concentrations of chlorides at the water or ground line. If the water-cement ratio is raised to 0.45, the concrete cover over the steel should be increased 1/2 in. Studies of durability of concrete (seawater exposure) showed that cements containing 5 to 8 percent tricalcium aluminate (C_3A) showed less cracking due to steel corrosion than cements with a C_3A content less than 5 percent (Verbeck, 1968).

Permeability is reduced by increased hydration of the cement. Concrete should be cured properly until at least 90 percent of the design strength has developed.

Table 2

Partial List of Deleterious Aggregates

Andesites and tuffs
Chalcedonic cherts
Dacites and tuffs
Fractured, strained, and
  inclusion-filled quartz
  and quartzites
Opaline cherts
Opaline concretions
Phyllites
Quartzose cherts
Rhyolites and tuffs
Siliceous dolomites
Siliceous limestones
Siliceous shales

Concrete cover over reinforcing steel should be adequate. In a well-cured concrete with low water-cement ratio, the depth of carbonation (calcium hydroxide is converted to calcium carbonate by atmospheric carbonation which destroys protective oxide film on the surface of the steel) is unlikely to exceed 25 mm, and therefore, a concrete cover of 25 to 40 mm over reinforcing bars should be adequate in most instances (Mindness and Young, 1981). Where more severe conditions of exposures are encountered or concrete with fairly high permeability is used, the cover should be increased at least 50 mm (Mindness and Young, 1981). Protection against penetration of salts to reinforcing steel in seawater exposure is 3 in., while the American Association of State Highway and Transportation Officials (AASHTO) recommends 4 in. except for precast piles.

In addition, other practices have to be followed to minimize corrosion. These are good concreting practices (workmanship). good drainage, and good specifications and inspection.

Good workmanship is a most important factor in securing uniform concrete of low permeability. This includes good consolidation and finishing practices, and precaution against segregation.

In areas of severe exposures, particular attention should be given to design details dealing with drainage to insure that the water will drain.

The passive oxide film on steel can be destroyed by chloride ions. Chlorides may enter the concrete from three major sources: (1) admixtures ($CaCl_2$), (2) deicing salts, and (3) seawater. ACI Committee 201 (ACI, 1977) suggests the following limits for chloride ion (Cl-) in concrete prior to service exposure, expressed as a percent by weight of cement.

1. Prestressed concrete	0.06 percent
2. Conventionally reinforced concrete in a moist environment and exposed to chloride	0.10 percent
3. Conventionally reinforced concrete in a moist environment but not exposed to chloride	0.15 percent
4. Above ground building construction where the concrete will stay dry (does not include locations where the concrete will be occasionally wetted--such as kitchens, parking garages, and waterfront structures)	No limit for corrosion

These limits should be applied with good judgement because other factors such as moisture and oxygen are necessary for electrochemical corrosion.

3. Recommendations for Minimizing Adverse Effects on Long Term Durability of Concrete

The following practices and precautions are recommended to provide durable concrete for aboveground engineered disposal facilities using portland cement concrete as the primary construction material.

3.1 Frost Action

The following items compose the recommendations to overcome frost damage.

3.1.1 Design the structure to minimize exposure to moisture. The building geometry must provide good drainage, with no surface that will provide for potential ponding. Therefore, use a sloped roof rather than a flat roof. Floor slabs must have a vapor barrier between the slabs and grade. Unnecessary joints must be eliminated.

3.1.2 Use low water-cement ratio. For structures of this type the water-cement ratio should not exceed 0.50.

3.1.3 Provide air entrainment in the mixture. It is recommended that air-entrained concrete be used for this construction and Table 3 shows the recommended air contents derived from ASTM (1977).

3.1.4 Use only suitable materials.

3.1.4.1 Cement. The several types of portland and blended cements, in properly proportioned and produced air-entrained concrete, will provide for resistance to cyclic freezing. However, to resist severe sulfate attack, Type V is required. Therefore, for this added protection, Type V conforming to ASTM C 150 is recommended.

3.1.4.2 Aggregate. The aggregates used for this construction should be the very best available, as long as it is cost-effective to obtain them. Careful judgement must be used in deciding the cost-effectiveness factors considering the nature of the material to be disposed. The aggregates should be thoroughly characterized by the physical tests required, i.e., petrographic examination, absorption, specific gravity, soundness tests, and determination of pore structure. These tests are described in the Handbook for Concrete and Cement (US Army Engineer Waterways Experiment Station, 1949).

Table 3

Recommended Air Contents for Freeze-Thaw Resistance

Nominal Maximum Aggregate Size		Air Content, Percent	
mm	(in.)	Moderate Exposure	Severe Exposure
9.5	(3/8)	6	7.5
12.5	(1/2)	5.5	7
19.0	(3/4)	5	6
37.5	(1-1/2)	4.5	5.5
75	(3)	3.5	4.5
150	(6)	3	4

3.1.4.3 Admixtures. Air-entraining admixtures should conform to ASTM C 260.

3.1.5 Use proper curing. Proper curing procedures and materials are required for durable concrete; they should comply with ACI Standard 308-81 (ACI, 1981). Depending on the structural member being cured, the techniques of inundation, water spray, wet burlap, plastic membrane, and sprayed-on membrane are recommended. The curing period should be that established in the laboratory which achieves a specified strength with that particular curing technique.

3.1.6 Use sound construction practices. Good construction practices should be implemented to obtain durable concrete. These include proper mixing, placing, handling, and consolidating of the concrete; protection against extreme temperatures; good forming techniques; use of a form material that will give a smooth dense finished surface; proper curing, especially after form removal; and immediate repair of any surface defects.

3.2 Aggressive Chemical Exposure

Protection against sulfates in the soil or groundwater is achieved by the use of sulfate-resistant cement in dense, high quality concrete with a low water-cement ratio. Table 4 provides certain recommendations for sulfate protection taken from ASTM (1977).

Protection against mild acid attack is achieved by the use of a dense concrete with a low water-cement ratio. However, surface coatings or treatments are required to protect against groundwater, soil, or accidental spills containing high concentrations of acids. ACI Committee 515 (ACI, 1974) has recommended certain barrier coatings for concrete under certain conditions. Table 5 gives recommendations for dampproofing coatings and Table 6 gives recommendations for protective barrier systems. Tables 5 and 6 were taken from ACI (1974).

3.3 Abrasion

Abrasion resistant concrete surfaces will be achieved by implementation of the following measures.

3.3.1 Use low water-cement ratio.

3.3.2 Use well-graded, hard, tough fine and coarse aggregates, with a maximum size of 1 in., meeting the requirements of ASTM C 33 (ASTM, 1981).

3.3.3 Use the lowest slump concrete that is practical for the working conditions (maximum 3 in., 1 in. for toppings).

3.3.4 Air content should be consistent with exposure conditions.

3.3.5 Use a topping layer over the main slab if severe wearing conditions are anticipated.

3.3.6 Finish (float and trowel) the surface only after the surface has lost its sheen.

3.3.7 Vacuum dewatering techniques can be used to remove excess water immediately after placing, resulting in a more dense concrete with increased strength and surface enhancement against wear.

3.3.8 Curing techniques of water spray, damp burlap, or cotton mats are recommended and the curing should be for 7 days.

3.4 Reactive Aggregates

3.4.1 Avoid alkali-reactive aggregates. If possible, reactive aggregates should not be used. However, if their use is unavoidable, they should only be used with low-alkali cement (maximum 0.60 percent equivalent Na_2O).

3.4.2 Determine alkali-carbonate reactivity and use measures to reduce the effects of this reaction.

3.4.2.1 Avoid reactive rocks.

3.4.2.2 Dilute the reactive rocks by the inclusion of nonreactive rocks.

3.4.2.3 Use low alkali cement.

3.5 Corrosion of Embedded Materials

The following measures should be employed to protect embedded items from corrosion:

3.5.1 Use low water-cement ratio.

3.5.2 Avoid honeycombing (provide good consolidation).

3.5.3 Use adequate concrete cover.

3.5.4 Design against structural cracks.

3.5.5 Keep chloride content below permissible values.

3.5.6 Provide protective coating on the concrete.

3.5.7 Provide coating on the steel.

3.5.8 Use good curing techniques.

Table 4

Protection of Concrete Subject to Sulfate Attack

Exposure	Sulfate in Water, ppm	Type Cement Required	Recommended Water-Cement Ratio, max.
Severe to very severe	1,500 to 10,000 and greater	Type V	0.45
Mild to moderate	150 to 1,500	Type II IP(MS) IS(MS)	0.50

Table 5

Recommended Dampproofing Materials and Techniques

Recommended Material or Technique	Siting Condition: Above Grade		Siting Condition: Covered or Buried	
	Ext. Face	Int. Face	Ext. Face	Int. Face
Portland cement Paint (water based)	X	X	/	X
Asphalt (cold applied)	X	X	X	//
Latex Paint (PVC)	X	X	/	X
Epoxy Paint (two-component)	X	X	/	X
Chlorinated Rubber Paint(solvent based)	X	X	/	X
Polyurethane Paint (moisture-cured or two-component)	X	X	/	X

/Exterior coating also required (see list in this table for other recommended materials).

//Interior coating also recommended (see list in this table for other recommended materials).

Table 6

Protective Barrier Systems in Chemical Environment

Exposure	Protection Against: Barrier System	Protection Against: Expected Attack
Severe	Composite system of: (1) Asphalt membrane covered with acid-proof brick and chemical-resistant mortar (greater than 6 mm thick)	Concentrated acid or acid/solvent material
	(2) Epoxy system (sand filled) topped with unfilled pigmented epoxy (0.5 mm to 6.75 mm thick)	Water, dilute acids, strong alkalies, and salt solutions
Severe	Neoprene sheet (precured, PVC sheet (plasticized), glass-reinforced (GR) epoxy, GR polyester (0.5 mm to 6 mm thick)	Organic acids (ph$<$3), salt solutions, strong alkalies
Moderate	Bituminous materials, sand-filled systems of epoxy, polyester or polyurethane (3 mm to 9 mm thick)	Abrasion and dilute acids (intermittent exposure)
Mild	Asphalt, chlorinated rubber, epoxy, vinyl, polyurethane, neoprene, coal tar, coal tar epoxy, coal tar urethane, styrene-acrylic copolymer, acrylic, polyvinyl butyral	Salts (such as deicing), frost damage, solutions with ph$>$4

3.6 Covered Versus Aboveground Structure

The recommendations presented so far have been applicable to aboveground structures. However, if a structure is covered, the information in Tables 5 and 6 must be put to use. The details of the materials and practices will be dictated by the characterization of the cover material. All other recommendations, as shown for the aboveground case, are applicable for underground structures.

3.7 Testing of Component Materials and Final Mixture

Once a decision has been made to construct an engineered disposal facility at a particular location, a test program should be designed and specified that will result in the use of the very best materials to produce the most durable concrete possible. The program should be designed so that the carefully selected components are fully characterized after having been thoroughly tested. The concrete composed of these components should also be fully characterized as to its response to the particular environment.

This program should be followed, once construction begins, with a carefully planned program of quality control and quality assurance. This will insure that the proper components will be used to produce a quality product capable of the high level of durability required.

4. Summary and Conclusions

Adherence to the guidelines and recommendations contained and referenced herein, along with good practices of production and construction, will produce a durable concrete capable of long life. The service life will be further enhanced if proper and timely repair and maintenance procedures are employed, should their need arise. There is no mathematical model that can predict service life of a structure, but by producing the best concrete possible and employing the best construction practices, the implication is that the material and structure will function for many years.

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13. ABSTRACT (200 words or less)

The study reported herein contains the results of Task 2a (Technical Requirements for Belowground Vault Disposal of Low-Level Radioactive Waste) of a four-task study entitled "Criteria for Evaluating Engineered Facilities." The overall objective of this study is to ensure that the criteria needed to evaluate five alternative low-level radioactive waste (LLW) disposal methods are available potential license applicants. The belowground vault disposal alternative is one of several methods that may be proposed for disposal of low-level radioactive waste. In this report, the term below-ground vault disposal refers to a near-surface disposal alternative in which the wastes would be disposed of in vaults constructed below ground in excavations and covered with soil. The experience and knowledge gained with this method are described and updated in this report. A generic description of the features and components and operation of a belowground vault disposal facility is provided. Features and components that could enhance the long-term performance are described, including site conditions for which they would be applicable. The applicability of existing criteria developed for near-surface disposal (10 CFR Part 61 Subpart D) to the belowground vault disposal method, as assessed in Task 1, are reassessed herein. With few exceptions, these criteria were found to be applicable in the reassessment. These conclusions differ slightly from the Task 1 findings.

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