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CRITERIA FOR GREATER CONFINEMENT OF RADIOACTIVE WASTES AT ARID WESTERN SITES

MAY 1981

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UNDER EG&G IDAHO SUBCONTRACT NO.K 1847

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May 1981

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ABSTRACT

This document provides a set of criteria and standards for greater confinement disposal (GCD) of low-level waste as an alternative to shallow land burial or deep geologic disposal for certain types of waste; i.e., disposal at depths sufficient to effectively eliminate intrusion by flora and fauna, minimize the possibility of inadvertent intrusion by man, minimize or eliminate the occurrence of other natural surface effects including wind and water erosion, and reduce the pathway for exposure by optimizing the depth for natural confinement. The criteria and standards are discussed relative to seven major areas: radiation exposure protection, characterization of waste, transportation and handling, site selection, engineering, general facility requirements, and administration. The document addresses the objectives or goals of burial at intermediate depths to provide greater confinement, and its advantages and disadvantages compared to shallow land burial. Additionally, the document describes a generic greater confinement disposal facility (GCDF), and discusses as well as evaluates the various interrelating factors which must be considered in the selection of a viable site and in the development of GCDF design and performance criteria.

Methods are developed for evaluating and ranking the importance of the factors based on health and safety, their potential impact on cost, and the uncertainty and/or difficulty in measurement and control of the factors. It also provides the methodology and analysis used to determine the various site-specific waste concentration acceptance standards (in the form of area disposal concentration limits) as well as design and engineering standards. It also illustrates the methodology used to determine the optimal or preferred depth of disposal under expected arid site conditions and alternative wet or irrigated site conditions. In addition, an example calculation demonstrates the application of the waste area concentration limits at an arid or humid GCDF in determining the allowable waste inventory capacity of a particular site and the loading capacity of a waste disposal cell.

CONTENTS

CONTENTS (Cont)

CONTENTS (Cont)

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 PURPOSE

The purpose of this report is to enumerate the criteria and standards for greater confinement disposal of low-level, solid, radioactive waste; i.e., disposal at depths sufficient to effectively eliminate intrusion by flora and fauna and substantially lower the possibility of inadvertent human intrusion. The name proposed for this enhanced subsurface disposal concept is greater confinement disposal or GCD. (The concept has been described in References 1 and 2 previously as intermediate depth burial or IDB). The criteria and standards are particularly oriented toward the design and operation of a generic greater confinement disposal facility (GCDF) at an arid western site. These criteria are formulated to enhance protection of the health and safety of the general public and future generations. In many respects these criteria are an extension of existing shallow land burial (SLB) criteria which are in force today. Greater confinement disposal expands on the current practices and provides incentives for a cost effective long-term solution. Since both disposal methods (GCD and SLB) deal with disposal of low-level waste and both have the same goal of protecting the public health and safety, it is logical that any new way of extending this goal to future generations should incorporate those points which have been demonstrated and shown to be acceptable. The criteria are based upon the data and information available in government publications and technical literature.

The specific objectives of the document are summarized as follows:

- Identify and technically define pertinent generic factors or criteria which should be considered in the selection of a site for a GCDF and the factors which should be considered in evaluating the safety, efficiency, and effectiveness of constructing and operating such a facility.
- Determine and document the relative importance of the factors.
- Define and describe pertinent parameters and identify their interrelationships and interdependencies with other factors.

The development of these criteria is the first step in the demonstration of the greater confinement disposal concept and preliminary to the development of site-specific design standards and the design and construction of a test facility (Reference 1).

1.2 OVERVIEW

Since the beginning of the atomic energy program in the United States, it has been the practice of the nuclear waste generators to dispose of low-level radioactive solid waste in shallow pits or trenches with the upper surface of the waste within one to three meters of the land surface. This practice is still being carried out with the exception that, since 1970, DOE waste containing greater than 10 nCi of transuranic materials per gram is classified as transuranic waste and is placed in retrievable storage. It is anticipated that this transuranic waste will be disposed in the future by some means other than SLB. Pre-1970 waste disposal sites containing transuranic waste are being studied by DOE for possible remedial action.

The greatest long-range potential for radiation exposure to mankind from radioactive wastes in shallow land burial does not lie, as generally believed, in contamination of irrigation or potable water supplies. In relating to conditions at arid disposal sites (Reference 3), Leddicotte has stated that this pathway (groundwater flow to a surface stream or well) "...is by far the least important of all plausible pathways. The reason for this unimportance is due to such mechanisms as (1) radioactivity retention within the waste and soil, (2) decay of radioactivity during migration, and (3) water course dilution." For humid sites, conditions such as fracture flow, reduced retention of waste in soil, etc., may increase the importance of the groundwater pathway for exposure. This emphasizes the advantages of GCD at arid sites as compared to humid sites. As long as the surface area over and adjacent to a waste burial site can be isolated and controlled by the institution responsible for its burial, the surface exposure pathways are essentially nonexistent, and the groundwater pathway may still represent the greatest potential though very small for radiation exposure to the general public. Unfortunately, no manmade institution will last forever, and the day will come when control of the surface area must be abandoned. When this happens, other pathways for exposure will become dominant over the groundwater pathway at SLB sites.

Several studies (e.g., References 2, 3, and 4) have shown that the potential dose and risk to man due to ingestion of food grown on contaminated soil or inhalation of contaminated dust resulting from near-surface waste disposal is greater than the dose and risk from drinking contaminated well water. Exposure scenarios such as plant root uptake, burrowing animals, surface erosion, and dust inhalation, however, are much less likely to be significant when the waste is buried deeper in the ground than present shallow land burial practices. Additionally, the possibility of a human "reclaimer" disturbing the waste should be greatly reduced with deeper burial of the waste. The reclaimer is taken to mean some future human being who inadvertently may disturb the radioactive waste in his efforts to make use of surface area over the buried waste. This reclamation activity may include such efforts as home building, agriculture, and recreation. Greater confinement disposal is not meant to prevent the determined efforts of the human who knows where the waste is buried and deliberately proceeds to intrude into the waste. It is expected that a human with sufficient technical knowledge to undertake intrusion at such depths would also have sufficient technical perception and ability to rationally protect himself against the possible hazards of such intrusion.

One of the greatest benefits that should be derived from deeper burial is a reduction of long-term institutional control of the surface area over the burial pits. With deeper disposal of radioactive waste, controls can be lifted sooner and the surface area released for unrestricted public activities.

Institutional control for a period of about 100 years, usually assumed for a shallow land burial site, assures that much of the disposed waste inventories will be reduced to non-hazardous levels through decay before the land is turned over to the public. While the majority of low-level waste can thus be safely buried in shallow land burial pits, some types of low-level waste may require greater isolation. For high specific-activity wastes, nuclides with minimal retention in soil, or longer-lived nuclides; a specified period of institutional control may be inadequate to reduce the potential health hazard or minimize or eliminate possible exposure pathways, if such wastes are buried too near the surface.

Greater confinement disposal of waste, in addition to minimizing or eliminating certain exposure pathways as discussed above, is designed to increase the period of natural confinement or retention of most nuclides within the ground. The period of retention depends on several factors, including the depth to the aquifer; the climatic conditions of the site (i.e., arid or humid); the soil hydrogeology; and the radiological, chemical, and physical characteristics of the waste. For conditions that exist at selected arid western sites, greater confinement disposal can be a plausible and cost-effective alternative to deep geologic disposal for certain types of waste requiring greater isolation than is provided by SLB.

Other technical and economic tradeoffs may exist between GCD and waste processing techniques being developed to produce waste forms with low leachability or to utilize higher integrity packaging.

The methodology given in Appendix A was developed to determine certain standards, including the optimal depth for burial of waste at a generic arid site and the allowable concentrations. The methodology could be applied similarly to sites with very different hydrologic and climatic conditions.

The methodology is based on a comparative evaluation of certain technical factors believed to be dominant in controlling the health impacts of typical low-level waste, including site hydrologic conditions, dispersion, waste inventory and integrity, and plausible pathways of exposure. It is recognized that any decision derived from the conclusions of this technical model must also be evaluated in light of economic considerations such as the cost and difficulty of excavating to greater depths and handling various types of wastes. Certain other technical factors not treated in this analysis, which may be the limiting factors if other than low-level waste is considered for greater confinement disposal, include criticality and thermal effects.

This document is intended to identify the criteria and standards required to permit safe disposal of radioactive wastes at greater depths, and to provide insights regarding the considerations important to disposal for greater confinement of radioactive wastes. The document is not intended to justify GCD or to determine what wastes should be selected for GCD.

1.3 ORGANIZATION

This report consists of six numbered chapters, including this introduction, and two appendices. The contents of the subsequent chapters and the appendices are as follows:

- Chapter 2 provides a brief discussion of terms which are fundamental to the understanding of the document. A more extensive glossary of terms is given following the appendices.
- Chapter 3 provides a description of the greater confinement disposal concept, its advantages and disadvantages, and a comparative discussion of present DOE arid western sites and the generic greater confinement disposal facility (GCDF).
- Chapter 4 summarizes the goals of low-level waste disposal by greater confinement disposal.
- Chapter 5 identifies and describes the factors pertinent to site selection and facility performance evaluation, and evaluates the relative importance and interrelationships of the various factors with regard to the health and safety of the public, cost, and the uncertainty in being able to measure and control the factors.
- Chapter 6 presents the criteria and standards for a generic GCDF at arid western sites, along with a brief discussion of each criterion.

- Appendix A provides the background and mathematical basis of the nuclide waste area concentration limits for arid western sites given in Table 6-1 and Section 6.2.6 and the optimum depth of disposal discussed in Section 6.5.2.

- Appendix B gives a sample calculation demonstrating the application of the nuclide area waste concentration limits given in Table 6-1 in determining the waste inventory capacity of a given site, the inventory loading capacity of a waste disposal cell, and the requirements for a buffer zone surrounding the site discussed in Section 6.5.3.

2. DOCUMENT TERMINOLOGY

The following definitions of key terms used in the low-level waste program are provided to clarify the usage in this document. A more extensive glossary is given following the appendices.

GOAL: A goal describes what is to be achieved--the end toward which effort is directed. Goals are generally expressed as qualitative statements of desirable conditions or actions. A goal may never be fully achieved; however, any effort expended toward that goal may still be worthwhile. An example of a goal is: Protect the public health and safety.

CRITERION: A criterion is a qualitative test of whether a goal has been met. For example, if the goal was to protect the public health and safety, a criterion could be: No member of the public shall be exposed to radiation levels at which discernible adverse effects are anticipated.

LOW-LEVEL WASTE (LLW): Low-level waste is that radioactive waste which is not defined by regulation to be high-level waste (HLW). HLW, as defined by NRC, includes spent fuel and aqueous wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for the reprocessing of irradiated reactor fuels. Radioactive wastes do not include naturally occurring materials such as coal, phosphates, or mine tailings which may contain radionuclides. Also excluded from LLW is that material which contains greater than 10 nanocuries of transuranic isotopes per gram of material.

Low-level waste includes a wide variety of materials and radiotoxicities. The vast majority of the bulk or volume of the waste contains only a small percentage of the total radioactivity. It has been estimated that over 90 percent of the radioactivity is contained in less than five percent of the waste volume (Reference 2, pp. 60, 61).

The physical and chemical properties of LLW also vary greatly. Some LLW candidates are in very stable physical and chemical forms, while others are very unstable. For some LLW the chemical toxicity is clearly greater than its radiotoxicity.

Most low-level waste comes from the following sources: government and military operations (51% by volume), operating nuclear power reactors (27%), institutions and industry (22%). The current rate of production of LLW in the United States is about 150,000 cubic meters per year. The bulk of the government wastes comes from DOE (National) laboratories and weapons production facilities. While a substantial amount of the waste previously placed in commercial disposal facilities is government waste, it is the current policy of DOE to send all DOE LLW to DOE facilities for storage or disposal (References 5 and 6).

QUANTITATIVE FACTORS: Quantitative factors are those factors for which numerical values can be determined and for which there is little uncertainty (e.g., soil depth).

QUALITATIVE FACTORS: Qualitative factors are those factors for which no numerical value can be determined or which, when values are assigned, have a high level of uncertainty (e.g., tectonic activity). Often, as a result of the uncertainty, the latter are evaluated in a subjective or qualitative manner.

STANDARD: A standard is a quantitative test of whether a criterion has been met. However, because it is sometimes very difficult to quantify all pertinent factors or areas of concern, a standard can also be a qualitative guideline to be used toward the development of quantitative tests, or can be a quantitative guideline to be used toward the development of a more definitive standard based on more extensive test results or analysis. An example of a standard that could be used to satisfy the criterion given as an example above is: No member of the public shall be exposed to ionizing radiation at levels exceeding 500 millirem per year.

3. DESCRIPTION OF THE GREATER CONFINEMENT DISPOSAL CONCEPT

Before a set of criteria can be proposed, it is necessary to define the concept and to establish the goals that are desirable for the GCD concept.

3.1 DEFINITION OF GREATER CONFINEMENT DISPOSAL

The purpose of GCD is to confine radioactive waste at a depth where deep-rooted plants, burrowing animals or inadvertent human reclaimers are not likely to penetrate. The following statement will therefore be used in this document to define greater confinement disposal:

> Greater confinement disposal is the emplacement of radioactive waste, with no expectation of retrieval, below grade level at sufficient depth to minimize surface effects (i.e., floods, erosion, etc.) on waste containment, and at sufficient depth that the consequence of any penetration of the waste by plant roots, burrowing animals, or normal use of the land by humans would be within acceptable limits.

3.2 COMPARISON OF GREATER CONFINEMENT DISPOSAL AND SHALLOW LAND BURIAL CONCEPTS

From an operational point of view, GCD is not radically different than shallow land burial. The concept involves placing the waste within the unconsolidated material (regolith) near the surface, but at some distance greater than practiced in SLB. The practical limits on how deep to bury the waste are related to the depth of the regolith and the depth to the water table. The advantages and disadvantages of GCD as an alternative to SLB or deep geologic disposal are summarized below.

Among the advantages are the following:

- GCD positions the waste farther from plant root systems and fauna than does SLB, minimizing plant and animal intrusion and the possibility of human intrusion (by definition, GCD is designed to minimize the inadvertent reclaimer scenario).
- The increased depth may prevent, or at least reduce, infiltrating water from surface runoff

from reaching the waste and reduce the amount of waste reaching the surface from upward migration.

- Stable temperatures at greater depths may also be an important consideration where the formation of gases containing radionuclides is a concern.

- Greater confinement disposal provides greater protection against uncovering the waste through surface erosional processes.

- GCD, particularly at arid sites, may be a technically viable and cost-effective alternative to deep geologic disposal for certain types of high specific activity wastes and wastes having long-lived nuclides, including transuranic wastes.

- The increased overburden may hasten consolidation of the site (i.e. reduce subsidence) contributing to reduced post closure maintenance costs for a GCD.

Among the possible disadvantages are the following:

- Increased costs because of the increased expense of excavation and handling.

- The greater confinement depth reduces the distance between the waste and the water table, increasing the potential for release to potable water supplies if water reaches the waste. This, however, may not be significant, depending on the absorbtive characteristics of the underlying strata, if the water table is sufficiently deep (>100 meters).

Other waste disposal considerations for GCD, such as transporting, stacking, and health and safety requirements, are similar to SLB requirements.

3.3 GENERIC ARID WESTERN GREATER CONFINEMENT DISPOSAL FACILITY

At the present time, there are four active DOE low-level radioactive waste disposal sites on government land in the arid west (i.e., those at Hanford, near Richland, Washington; Idaho National Engineering Laboratory, near Idaho Falls, Idaho; the Nevada Test Site, near Las Vegas, Nevada; and Los Alamos Scientific Laboratory in New Mexico). In addition, western commercial low-level waste burial sites are located at Beatty, Nevada, and Hanford, Washington. All of these sites utilize shallow land burial as the disposal method. Although these areas are geographically widely separated, they are remarkably alike in many aspects. All were originally located in desert regions characterized by low rainfall, low population, and deep water tables. Since the Hanford site was originally established, the population within a 5-mile band around the site has grown to over 300,000, so this area may no longer be considered a low population area.

It is likely that any new waste disposal facility in the West would be located at a similar remote desert site. Economic and sociopolitical considerations will probably dictate that any new waste disposal facility be located on land that is of very little potential value to man otherwise.

The generic GCDF is assumed to be typical of the DOE shallow land burial sites. It is located in a desert environment, has a thick vadose zone (unsaturated moisture region), relatively porous sandy soil, and low precipitation. (For a detailed listing of the specific parameters used in the nuclide migration analysis, see Appendix A.)

4. GOALS FOR GREATER CONFINEMENT DISPOSAL

The National Low-Level Waste Management Program Plan (Reference 7) and the Interagency Review Group (Reference 8) have made several recommendations pertaining to low-level waste management.

The following statements are based on these recommendations and are proposed as reasonable goals that are desirable for greater confinement waste disposal and management of low-level waste for the protection and safety of present and future generations. It is recognized that some goals may never be fully achieved. Continual striving towards those goals, however, will assure that the highest reasonable protection is achieved, consistent with realistic budget constraints, rather than the minimum.

The goals are summarized as follows:

- The impacts on man and his environment from disposing of radioactive wastes at greater depths shall be within the limits imposed by current regulations and shall not exceed the consequences anticipated by shallow land burial of wastes.
- Any requirement for active participation or resource commitment by future generations for the maintenance of the disposal facility shall be minimal.
- The impacts on man and his environment with regard to disposing of radioactive wastes at greater depths shall be minimized to the extent that the increase in resources committed to reducing those impacts is justified by the decrease in impacts.

5. FACTORS PERTINENT TO SITE SELECTION AND PERFORMANCE CRITERIA DEVELOPMENT

To develop criteria for GCDF site selection and performance, a number of pertinent factors should be considered. The factors shown on Table 5-1 list areas of concern that must be considered in developing the site selection and performance criteria.

The chapter is divided into two sections. Section 5.1 discusses the pertinent factors and their relationship to the criteria. It should be recognized that criteria that are primarily associated with the operation of the facility did not evolve from the list in Table 5-1 but are based upon similarities between that aspect of the greater confinement disposal concept and other land disposal facilities for radioactive waste. Section 5.2 evaluates and compares the relative importance of the factors listed in Section 5.1. The assignment of relative importance is somewhat subjective and may vary according to the interests and background of the assignor.

5.1 PERTINENT FACTORS

The factors listed in Table 5-1 are areas of concern that must be considered in the selection of a site for a GCDF. Public acceptance of a nuclear facility is not always based upon a quantitative analysis of the pertinent factors. Many factors involved in the decision-making process cannot be reduced to numbers or engineering data but are sometimes based on very qualitative or sociopolitical considerations. For the purpose of this discussion, the factors in Table 5-1 have been divided into two categories:

- Quantitative Factors are those factors for which numerical values can be determined and for which there is little uncertainty (e.g., soil depth).

- Qualitative Factors are those factors for which no numerical value can be determined or which, when values are assigned, have a high level of uncertainty (e.g., tectonic activity). Often, as a result of the uncertainty, the latter are evaluated in a subjective or qualitative manner.

5.1.1 Quantitative Factors

Distance Between the Waste and the Aquifer - The distance between the waste and the aquifer is only a partial measure of the ability of the site to contain the radioactive nuclides.

TABLE 5-1

FACTORS TO BE CONSIDERED FOR SITE SELECTION

Quantitative Factors	Qualitative Factors
● Distance between waste and aquifer (thickness of vadose zone)	● Potential mineralogical value of the land
● Subsurface hydrology	● Impacts on flora and fauna
● Surface hydrology (including flooding)	● Potential recreational value of land
● Physical and chemical characteristics of strata	● Potential archeological value of land
● Meteorology and climatology	● Ownership of land
● Demography	● Probable plant or animal intrusion
● Erosion	● Tectonic activity (including vulcanism)
● Soil cover depth	
● Proximity of public roads or facilities	
● Location of waste generators	
● Characteristics of waste	

A determination of whether the distance between the waste and aquifer or the distance from the surface to the aquifer is sufficient to permit burial of wastes at greater depths is dependent on many factors, including the hydrological and geological conditions at the site, the complexity of the geohydrological system, and the inventories and characteristics of the waste to be buried, among others. The prediction of nuclide migration to the aquifer depends on the ability to predict the velocity and direction of moisture flow within the strata separating them. If the underlying strata are highly fractured or contain large void spaces as might occur in limestone formations (caves) or basalt formations (lava tubes), it will be very difficult to predict water movement in such strata.

Similarly, the sorptive characteristics and permeability of the rock or soil will vary greatly between potential sites. Highly permeable, nonsorptive material such as gravel may require several meters of thickness to equal the retention of one meter of clay.

Subsurface Hydrology - Water is generally the major vehicle for nuclide movement below the level of root and animal penetration. If radioactive nuclides are able to enter an aquifer that is used for culinary or agricultural purposes, public exposures follow. To avoid unacceptable exposures, it is necessary to study the hydrogeologic features near a candidate site such that nuclide migration can be predicted. The age of the groundwater (as determined by Carbon 14 dating) is an important characteristic in evaluating the potential for nuclide migration via groundwater at a particular site (Reference 9).

Data on groundwater velocity and direction must be analyzed. Also, the volumetric flow rate and end uses of any stream or body of water into which the aquifer may empty must be evaluated. Vapor phase transport of water and certain nuclides such as tritium may also contribute importantly, particularly in unsaturated hydrologic areas where the existence of thermal gradients in underground strata develop phase instabilities. While it is possible to model this phenomenon, consideration of sites where vapor phase transport is believed important should probably be minimized because of the complexity of predicting the performance of such a site. A complete analysis will provide assurance that any potential release of radionuclides is within permissible levels. If, however, exposures are calculated to be above permissible levels, engineered barriers that will remain effective for the necessary time frame must be erected or the site must be rejected as a potential burial ground.

Surface Hydrology - Consideration of the surface features of a site must also be taken into account. A disposal site must not be located in or near surface water channels or near bodies of surface water that would be in danger of becoming contaminated. Arid regions are notorious for flash floods that suddenly wash down out of mountain canyons, eroding away unconsolidated soil or flooding areas that are normally dry. Paleohydrologic conditions as well as recent conditions must be considered to ascertain the risk of flood or to engineer adequate flood protection into the design.

Physical and Chemical Characteristics of Strata - This item is very closely related to the distance between waste and aquifer discussed earlier. The discussion concerning groundwater movement in the strata is also applicable here. The physical characteristics such as permeability, porosity, retardation, and degree of fracturing are of interest in modeling the movement of groundwater under the burial facility. Some chemical characteristics are equally important however, for predicting the mobility of the nuclides. Chemical characteristics of the strata such as acidity, chemical makeup and adsorptivity are also important considerations in determining the possible effects on nuclide movement. A site which is characterized by a complex geohydrologic system having many dominant characteristics contributing to nuclide mobility should probably be rejected on the basis of the analytical difficulty in predicting its performance. However an alternate site having a complex system of features which retard nuclide mobility and contributes to greater waste isolation may be an excellent site selection despite the analytical difficulty in predicting its performance.

Meteorology and Climatology - Dry climates are separated into two degrees of intensity, semiarid and arid. The division between humid and semiarid climates occurs where the ratio of precipitation to evaporation is less than one. The boundary between semiarid and arid is about one-half the amount of precipitation that locally divides semiarid from humid conditions. Therefore, for a GCDF located in an arid region, the evaporation rate would be at least double the precipitation rate. This means that it is unlikely that meteoric water would penetrate the waste and continue downward to the aquifer.

The absolute amount of rainfall that will produce humid conditions cannot be stated because it will vary with the mean annual temperature of an area. The amount of annual precipitation in the United States that will produce humid conditions varies from about 0.51 m in North Dakota to about 0.76 m in Texas. Less than 0.25 m of annual precipitation will produce a desert in almost any location (Reference 10).

In addition to rainfall and evaporation rates, other meteorological data for a candidate site must be considered. The velocity and direction of the wind (wind rose) should be examined to determine if an accident during waste handling operations could present an unacceptable exposure to downwind populations.

Such factors as temperature extremes, tornadoes, and snow accumulations are also important considerations. These items could strongly affect the operation and costs of the facility during the time it is open. After closure these factors no longer have an impact on the continued performance of the GCDF.

Potential climatic changes, although not likely over the short term, should be considered in the design and siting of a facility. Although natural climatic changes (e.g., changes in the mean annual precipitation) generally take thousands of years to manifest themselves, man-induced effects which behave like climatic changes (e.g., those due to irrigation) can take place in a short time period.

Demography - The population distribution surrounding a potential waste disposal site must be considered when setting site criteria. With intermediate depth burial, the risk to off-site populations should be negligible after the site is closed; however, the possibility of an airborne release during transportation and handling must be considered. The site must be located as far as practical from large population centers, so that the maximum credible handling accident will not give unacceptable population exposures. Generally, a consideration of population within an 80-kilometer (50-mile) radius will suffice for this calculation. In addition to the meteorology, the exposure calculated is dependent on waste form, concentration, and packaging integrity.

Future demography is more difficult to quantify. Forecasting population shifts far into the future is so difficult that very little confidence can be placed with it. However, it is desirable to consider such shifts and locate any GCDF in an area that is unlikely to be developed within the time that the waste will remain hazardous. It is assumed that the greater the distance that can be maintained between the waste and large population centers, the lower the probability will be of unacceptable population exposures.

Areas that are presently a considerable distance from large population centers, with a limited water supply, an unpleasant climate, soil unsuitable for agriculture, or that have any other features that are undesirable for human habitation are areas which are least likely to become centers of population development.

Demographic projections are possible for long periods into the future based on extrapolation of current demographic patterns. However, recent census data indicate the overwhelming uncertainty of such long-range predictions as evidenced by the unexpected shift of populations away from urban centers toward areas of lower population density. The factors contributing to such shifts in recent history, while recognizable after the fact, are too uncertain or indefinable to justify demographic projections beyond 100 years.

Erosion - Wind is an important agent of erosion in desert regions. Since the vegetation is generally widely spaced shrubs and salt-tolerant bushes, dust and sand can be swept up from the bare ground and removed from an area by the desert winds. Windblown materials are easily trapped by obstructions such as rocks or bushes to form dunes. The engineer can take advantage of this and change the surface area above a burial site from an area of depletion to an area of net deposition by placing rocks or resistant barriers on the surface after the site is closed.

Rain in the desert is usually of high intensity, short duration and local extent. Cloudbursts or convective thunderstorms over desert mountains usually bring most of the rain. Because the ground is almost bare, the rain runs off rapidly from slopes and may cause severe erosion, particularly on ground that has been disturbed and not yet returned to its primal stabilized condition.

The designer of a GCDF located in an arid region (the desert) must use care to avoid areas that are down gradient from mountain canyons where flash floods are likely to occur.

Soil Cover Depth - Greater confinement disposal is primarily aimed at placing the waste beyond the zone of probable intrusion by an inadvertent reclaimer, the roots of native plants, or the burrowing of terrestrial animals. Most previously published discussions of GCD (previously called intermediate depth burial) have suggested that this depth is a minimum of 10 m.

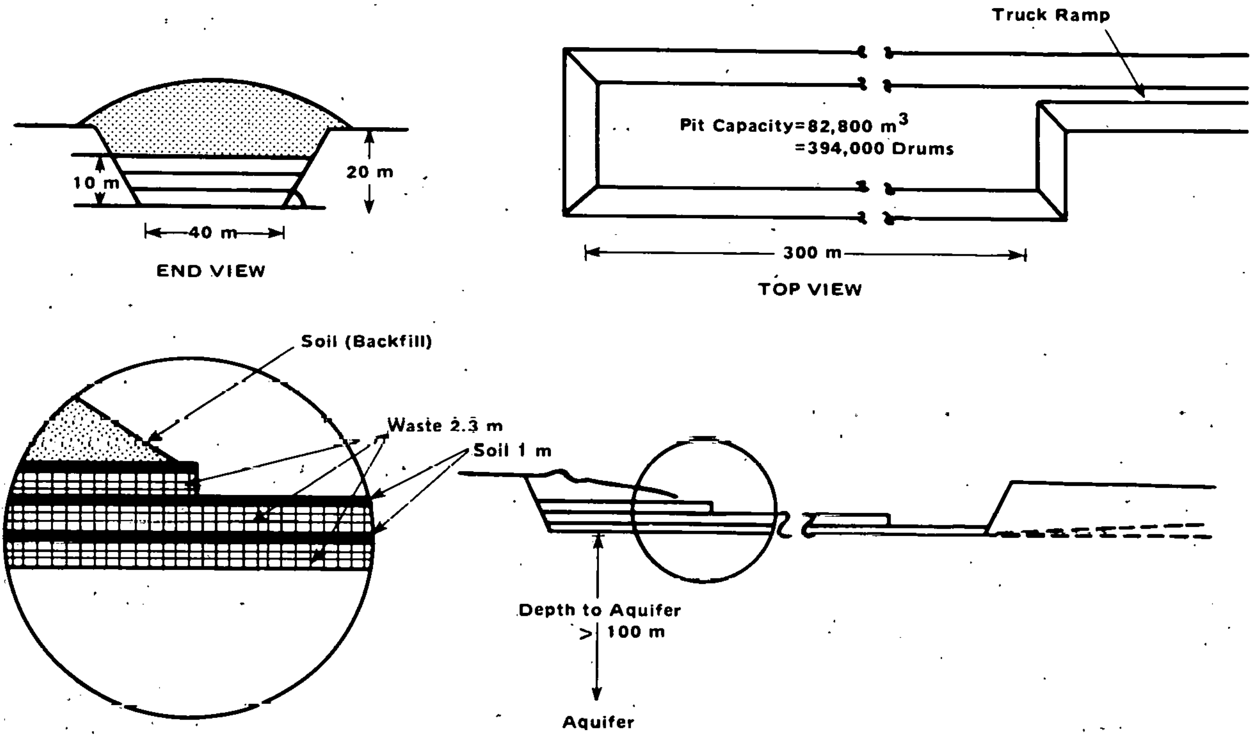
An optimal depth for waste burial was determined utilizing the methodology in Appendix A of this document. The methodology is based on comparative analyses at varying depths of the allowable concentrations of a typical reference low-level waste source that contributes, via release by competing exposure pathways, under possible but not highly probably worst case conditions to a maximum individual health impact of 500 mrem/yr. Under expected or normal conditions, the expected health impact should be less than 3 mrem/yr to the general public. The analyses were done for two site conditions or scenarios representing the expected site conditions at an arid western site, characterized by zero vertical water velocity and nominal dispersion, and the limiting case, contributing to a maximum individual dose of 500 mrem/yr which would be comparable to a scenario where irrigation was initiated above the burial site in conjunction with farming and raising of food crops or where a change to a humid climate permitted natural growth of crops. The analyses considered five exposure pathways--drinking well water pumped from an underground aquifer, ingestion of food crops contaminated by root uptake of nuclides which reached the surface via dispersion or mechanical disturbance (i.e., intrusion), inhalation of resuspended soil contaminated by nuclides which migrated to the surface, inhalation of radon gas, and direct exposure to contaminated surface soil. The optimal depth of 30 to 40 meters was determined for a generic arid western site having a surface-to-aquifer depth of 160 meters. Thus, a soil depth of 40 to 50 meters below the surface is required when taking into consideration the added thickness of the waste.

The cost of developing a GCDF is closely associated with soil depth. Excavation of unconsolidated material to a depth of 40 to 50 m below the surface can be accomplished at relatively moderate costs for burial pits and at relatively low cost (compared to deep geological burial) for an GCD borehole concept discussed later in this section. If, however, bedrock must be excavated to reach the required depth, the facility cost would be greatly magnified. The need for an impervious liner would be determined by the absorption properties of the native soil and the annual precipitation at a specific site.

<u>Proximity of Public Roads or Facilities</u> - Any public roads or other facilities which may involve the general public and which are in the vicinity of the disposal site must be evaluated. The principal concern is public exposure in the event of an unplanned radiation release to the atmosphere during the operating period.

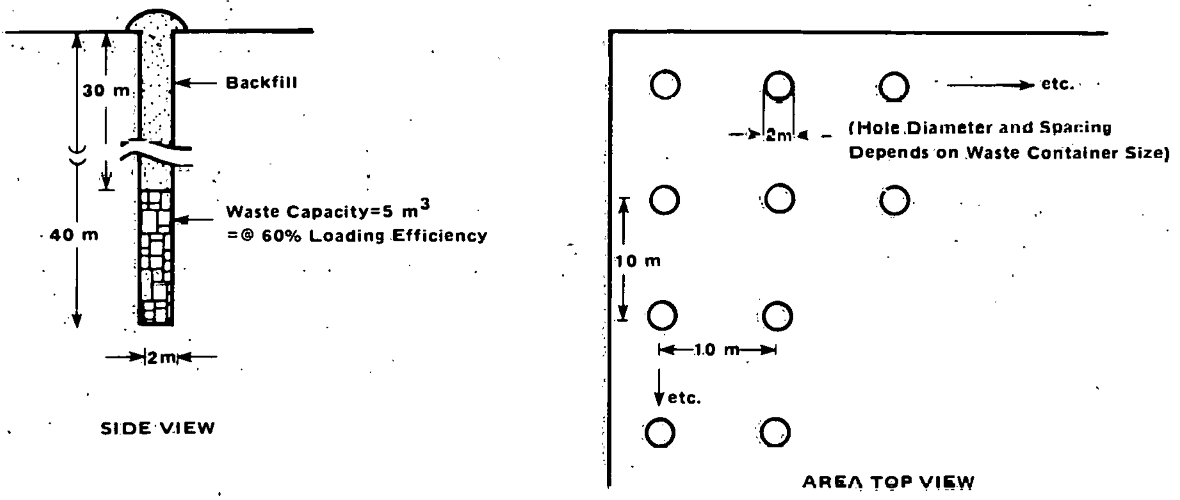
<u>Location of Waste Generators</u> - The location of the principal waste generators should be identified so that transportation risks across public highways or through population centers can be properly evaluated. Transportation routes may be selected which do not pass through large population centers. All other things being equal, it can be assumed that, in general, the greater the distance between the waste generator and the proposed disposal site, the greater the risk.

<u>Characteristics of Waste</u> - Several characteristics of the waste to be buried must be identified, such as the total volume to be buried, type(s) of containers, physical form of the waste, principal nuclides, nuclide concentrations, and leachability. Most of these characteristics would have no influence on the location of an GCDF, but they are very important parameters where design of the facility is concerned. For example, if the volume of the waste is large and the radiation level is low, the facility may be designed as an open pit. (See the top portion of Figure 5-1 showing the end, top, and cross-sectional views of a large volume burial pit.) On the other hand, if the volume is small and the radiation high, the design may call for a small diameter vertical shaft (borehole). (See the bottom portion of Figure 5-1 showing the borehole cross-sectional and top-view layout of a series of disposal shafts.) Where high specific activity and low specific activity wastes are being received, there may be a need for both of these concepts in the same facility. For example, a borehole or narrow trench could be excavated in the bottom of a large pit for disposal of high activity, low-level waste, thus minimizing the exposure potential to facility operators. (Note that the



(a) HIGH CAPACITY (HIGH VOLUME - LOW RADIATION) PIT CONCEPT AS ALTERNATIVE TO SHALLOW LAND BURIAL

(Dimensions Shown Are Typical)



(b) LOW CAPACITY (LOW VOLUME-HIGH RADIATION) BOREHOLE CONCEPT AS ALTERNATIVE TO SHALLOW LAND BURIAL

(Dimensions Shown Are Typical)

FIGURE 5-1 GREATER CONFINEMENT DISPOSAL FACILITY CONCEPTS dimensions and values shown in Figure 5-1 are typical and are not intended to reflect the design of a particular GCDF.)

5.1.2 Qualitative Factors

Potential Mineralogical Value of Land - This factor has significance in protecting future generations. Future generations should not be deprived by the present generation of access to mineral deposits which may someday be vital to their civilization but which may not presently be economically feasible to recover.

A mineralogical survey should be made of any proposed site. Arid desert sites may be underlain with significant deposits of such minerals as potash, colemanite (borax), halite (salt), coal, or natural gas. Recovery of shallow deposits of such resources could be severely restricted by the presence of a radioactive waste burial site. However, mining of deep deposits may be possible without disturbing the waste if its location is known at the time resource extraction begins.

Impacts on Flora and Fauna - Any new government construction project is required by federal law to examine the impact the construction may have on any rare and endangered species of plants or animals. Particularly in arid regions, where desert plants and animals are seldom consumed by the public, this factor, by itself, would have little or nothing to do with protecting the general public health. Nevertheless, it must be considered in order to comply with federal law.

The establishment of an area where human access is restricted, as will be the case for a GCDF, will often enhance the growth of most flora and fauna. However, it must be determined if the disposal site lies on a migratory route for such animals as deer or antelope or if it will have any impact on native plants or small animals.

Potential Recreational Value of Land - Under the assumption that a GCDF would be located on land restricted from public access during the period of operation and postclosure control, this factor has little to do with protecting the public health and safety. The item is considered because of its potential sociopolitical impacts and to facilitate public acceptance of the facility. In many areas, such as southern California, the deserts are becoming increasingly popular for recreational activities such as camping, motorbike riding, rockhounding, sunbathing, dune buggy riding, etc. An area that has no permanent residents may have hundreds of weekend visitors. Opposition to the location of a GCDF in a particular area could result in many costly delays as a result of public hearings. This factor could have a material effect on the site selection and operation of a GCDF.

After the period of control, the depth of waste confinement is sufficient to adequately shield any recreational visitors to the site from possible direct whole body exposure from the buried waste. Even for the small concentration of nuclides that may migrate to the surface via dispersion, the impact of direct exposure to such would be extremely small because the residence time of a visitor to the site would be extremely small.

Potential Archeological Value of Land - For all new federal construction projects, the Historic Preservation Act mandates the determination of potential effects on cultural resources and the preservation of sites in situ or the preservation of historical and archeological data that might be irretrievably lost.

An archeological survey must be made of a candidate disposal site to assure that important archeological material would not be lost. Potential effects are not limited to the localities directly modified by the project, but may also include ancillary features such as access roads, power lines, or construction crew camps.

This factor also is not concerned with public health and safety but is important because of its sociopolitical impacts and for compliance with federal law.

Ownership of Land - The siting of a GCDF should be on land that is owned by the federal government or could be acquired by the federal government. This will assure that the waste can be isolated from the general public for as long as may be deemed necessary to protect the public health and safety. For shallow land burial this institutional control has been proposed to be necessary for 100 years.

With deeper burial depth, it is expected that the surface area could be returned to unrestricted public use in less than 100 years after waste burial has been completed and the surface stabilized. This point has been regarded by many as a major advantage of GCD over shallow land burial for low-level waste disposal.

Probable Plant or Animal Intrusion - Greater confinement disposal generally implies burial at a depth below any possible plant root intrusion or animal burrowing. However, the plant and animal community must be examined to ensure that no unusual species exist in the area which could intrude on the waste. It is, however, the ultimate effect of intrusion in terms of its risk to man rather than its absolute prevention that is of concern.

Intrusion into the waste may occur without causing adverse effects. For example, the badger is notorious for digging deep if something attracts it. However, the materials usually found in radioactive waste are not materials the badger is likely to ingest intentionally. Very small quantities of contamination on the badgers' fur would not constitute a significant threat of exposure to human beings.

Tectonic Activity - The probability of tectonic activity affecting a burial facility is extremely low. A severe earthquake centered near the GCDF could destroy surface handling equipment and support facilities, but even then it would probably not result in a major release of contamination. The eruption of a new volcano directly beneath a burial site could spread contamination over a wide area but such an event is extremely unlikely. Even in this unlikely event, the relative impact of waste spread over a wide area would be negligible compared to the impact of the volcano itself. The most plausible event related to tectonic activity that could affect the GCDF would be a change in groundwater flow patterns due to fault slippage. Water coming in contact with the waste could transport radioactive nuclides to the surface and result in exposures to surrounding populations.

Generally, most severe tectonic activity occurs in rather well-defined zones which can easily be avoided. It is easier and safer to avoid active earthquake and volcanic areas than to try to engineer barriers against them.

5.2 RELATIVE IMPORTANCE

The factors pertinent to site selection and criteria development are ranked in Table 5-2. Three attributes are considered which are related to the goals identified in Chapter 4. They are the following:

- The relative importance of the factor in affecting the health and safety of the public
- The importance of the factor on the cost of the waste disposal facility or system
- The uncertainty in the ability to measure, forecast, or control the effect of the factor on the performance of the waste disposal system over the period the waste may remain hazardous

Tables 5-3 through 5-5 define the method for ranking each factor according to the three attribute categories defined above.

The first attribute reflects the importance of a site selection factor in determining that ". . . the impacts on man and his environment . . . do not exceed consequences deemed to be acceptable to the present generation."

TABLE 5-2

RANKING OF FACTORS PERTINENT TO SITE SELECTION[a]

		Health and Safety Importance	Cost Importance	Difficulty in Measuring, Forecasting and Control
1.	Distance Between Waste and Aquifer	5	1	3
2.	Physical and Chemical Characteristics of Strata	5	3	4
3.	Characteristics of Waste	3	3	4
4.	Subsurface Hydrology	5	1	3
5.	Surface Hydrology	4	2	3
6.	Erosion	5	1	2
7.	Soil Cover Depth	3	3	1
8.	Meteorology and Climatology	4	2	3
9.	Demography	5	3	5
10.	Location of Waste Generators	3	3	2
11.	Proximity of Public Roads	2	2	1
12.	Tectonic Activity	3	1	3
13.	Probable Plant or Animal Intrusion	4	1	3
14.	Potential Mineralogical Value	5	3	3
15.	Potential Archeological Value	1	1	2
16.	Ownership of Land	1	4	1
17.	Flora and Fauna Impacts	1	1	2
18.	Potential Recreational Value of the Land	3	1	3

Ranking Key: 1 = Least importance 5 = Most importance

(a) The above data are graphically presented in Figures 5-2 and 5-3 on pages 5-17 and 5-19, respectively. The data represent the summary analysis of responses of a review group of experts subject to the weighted interpretation of the preparers.

TABLE 5-3

DEFINITION OF RANKINGS FOR HEALTH AND SAFETY ATTRIBUTES

Attribute	Ranking	Definition
Health and Safety Importance	5	The factor is a controlling parameter in affecting the ability of the waste burial site to perform satisfactorily in minimizing the health and safety impacts to the public, both present and future. The ability of man to control or modify the factor is very limited. Overall effects are sensitive to minor changes in the factor.
	4	The factor is also a controlling parameter as above but man may have some control over the factor. Overall effects are less sensitive to minor changes in the factor.
	3	The factor is important, but not controlling, in affecting the ability of the site to perform satisfactorily. Man has reasonable control over the factor. A one-to-one correspondence exists between overall effects and changes in the factor.
	2	The factor has minor importance in affecting the performance of the site. Man has considerable control over the factor. The overall effects are only slightly affected by changes in the factor.
	1	The factor has relatively no importance in affecting the ability of the site to adequately provide health and safety protection to the public at large. Man's control over this factor is therefore not important. The predictable performance of the site is unaffected by this factor.

TABLE 5-4

DEFINITION OF COST RANKINGS

Attribute	Ranking	Definition
Cost Importance	5	Minor changes in the factor can affect the cost of developing an IDBF at that location by several orders of magnitude; i.e., an inappropriate factor value would make the costs of developing a site prohibitive.
	4	A change in the factor or an inappropriate condition has an important impact on cost. It can be compensated by engineering but with an order-of-magnitude increase in cost.
	3	A change in the factor has a moderate but approximately one-to-one effect on cost. Engineering or man's judgment in decision-making can be used in a cost-effective manner to reduce the impacts of this factor.
	2	The cost of developing a GCDF is affected only to a slight degree by this factor. Man can easily affect the impact of the factor with only a minor effect on cost.
	1	The factor has virtually no foreseeable effect on the cost of developing a GCDF at a specific location, as the cost of a facility would be constant regardless of a change in the factor.

TABLE 5-5

DEFINITION OF RANKING DIFFICULTY IN MEASURING, FORECASTING AND CONTROLLING THE EFFECT OF THE FACTOR ON THE PERFORMANCE OF A WASTE DISPOSAL SYSTEM

Attribute	Ranking	Definition
Difficulty in Measuring, Forecasting, or Control of Factor	5	There exists a high degree of uncertainty or difficulty in man's ability to control the factor or its effects on the performance of a waste disposal system.
	4	A moderate degree of uncertainty or difficulty exists but man may have limited control over the effects of this factor on the performance of the GCDF.
	3	Man, by reasonable judgment in site selection and decision-making, has moderate control over the effects of this factor on predictable site performance, although there exists a nominal degree of uncertainty regarding the factor.
	2	Although a degree of difficulty exists in measuring, forecasting, or controlling this factor, it is well within man's ability to measure and control its effects satisfactorily.
	1	The control of this factor is either unimportant in affecting the performance of the GCD site, or the factor is easily measured and expected to be constant over the period during which the waste may remain hazardous, or man has total control over the factor through either engineering or judgment in selecting sites with appropriate factors.

The second attribute reflects the goal that waste disposal activities not produce an "irreversible commitment of resources on future generations," and the goal that "an incremental increase in resources committed to reducing impacts is justified by an incremental decrease in impacts."

The third attribute describes the ability to accurately measure, forecast, or control the impacts on man and his environment for the period the waste may remain hazardous.

To illustrate the costs and benefits of the GCD site selection factors, Figure 5-2 plots each factor in terms of the two attributes--health and safety importance and cost importance. A larger circle around a factor identity number represents a higher perceived degree of uncertainty in measuring, forecasting, or controlling over the period during which the waste may be hazardous. The factors cluster in three groups which are identified in Table 5-6 by the "Figure 5-2 Factor Grouping" headings. The groups are characterized as follows in the column on the left side of the table:

- Those factors demonstrating high overall importance with respect both to health and safety and to impacts on costs; i.e., demography, physical and chemical characteristics of the strata, potential mineralogical value of the land, location of waste generators, characteristics of waste, and soil cover depth. (In the case of waste generator locations, the period of concern is the 30 or so years of disposal site operation.)

- Those factors having high health and safety importance but little impact on system costs; i.e., distance between the waste and the aquifer, subsurface hydrology, surface hydrology, erosion, meteorology, etc.

- Those factors having only minor impact on health and safety; i.e., proximity to public roads, ownership of land, potential archeological value, and flora and fauna impacts. One of the factors--ownership of land--may have a moderate impact on cost.

Figure 5-2 shows that variations in most factors are perceived to have only small to moderate impacts on system costs. Only three of the more important health and safety factors (those in the upper right cluster) are also judged to have a moderate impact on cost. One of these, demography, is also quite difficult to forecast because of the uncertainty of future shifts in population. In other words, the cost of constructing and operating a radioactive waste disposal facility at a given site is relatively independent of location, assuming,

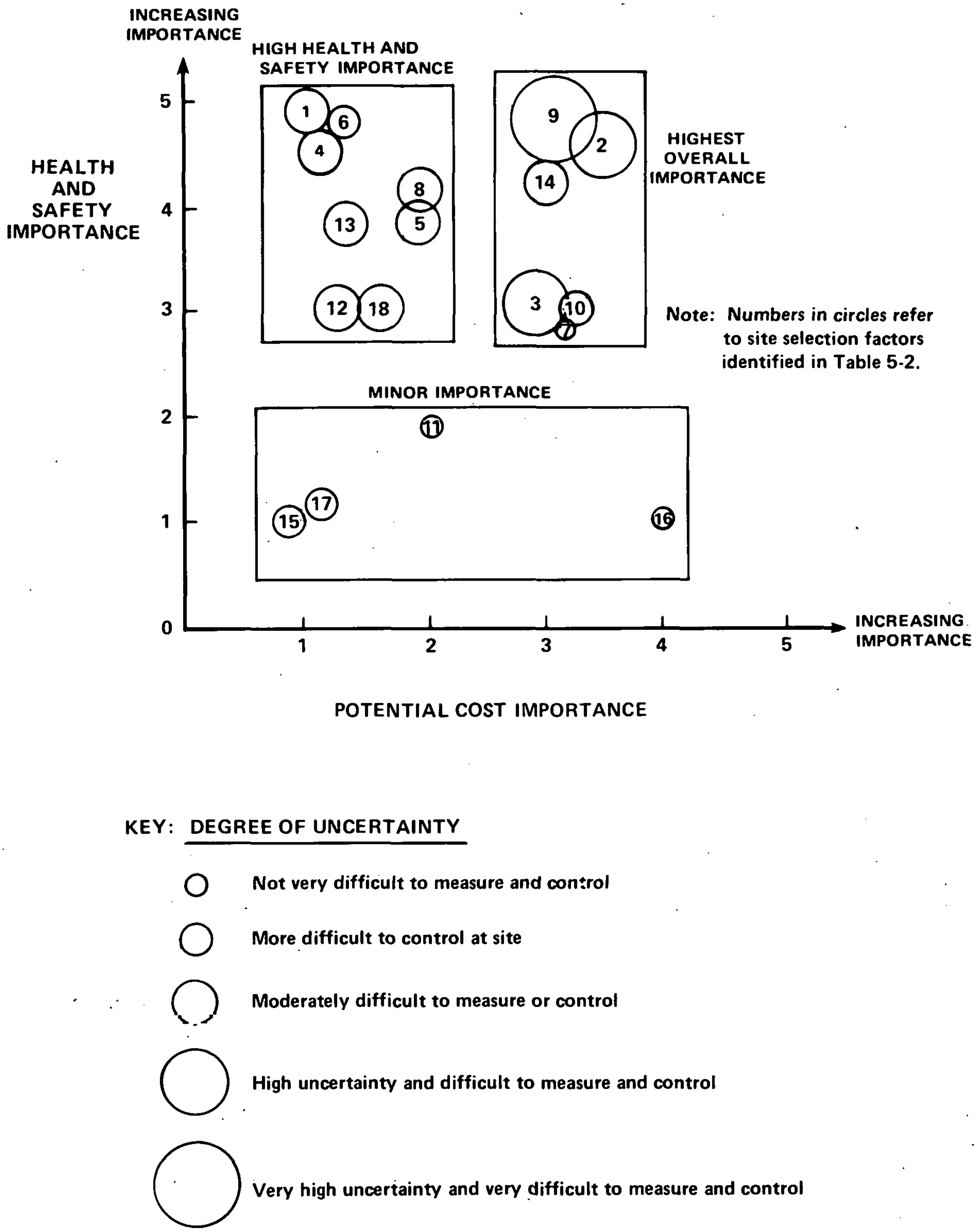


FIGURE 5-2 IMPORTANCE OF SITE SELECTION FACTORS RELATIVE TO HEALTH AND SAFETY AND COST

TABLE 5-6

SUMMARY OF RANKINGS OF SITE SELECTION FACTORS

Figure 5-2 Factor Groupings	Figure 5-3 Factor Groupings
Ranking of factors in Figure 5-2 by importance to health and safety and cost.	Ranking of factors in Figure 5-3 by importance and significance to health and safety only
High Health, Safety and Cost Importance	Most Significant Factors
Demography Physical and chemical characteristics of strata Potential mineralogical value Location of waste generators Characteristics of waste Soil cover depth	Demography Physical and chemical characteristics of strata Characteristics of waste
High Health and Safety Importance	Significant Factors with Moderate Difficulty in Measuring, Forecasting, and Control
Distance between waste and aquifer Subsurface hydrology Erosion Meteorology and climatology Probable plant or animal intrusion Tectonic activity Surface hydrology Potential recreational value	Potential mineralogical value Distance between waste and aquifer Subsurface hydrology Surface hydrology Meteorology and climatology Probable plant and animal intrusion Tectonic activity Location of waste generators Erosion Potential recreational value
	Important and Well-Understood Factors
	Soil cover depth
Minor Importance	Minor Importance
Proximity to public roads Ownership of land Potential archeological value Flora and fauna impacts	Proximity to public roads Ownership of land Potential archeological value Flora and fauna impacts

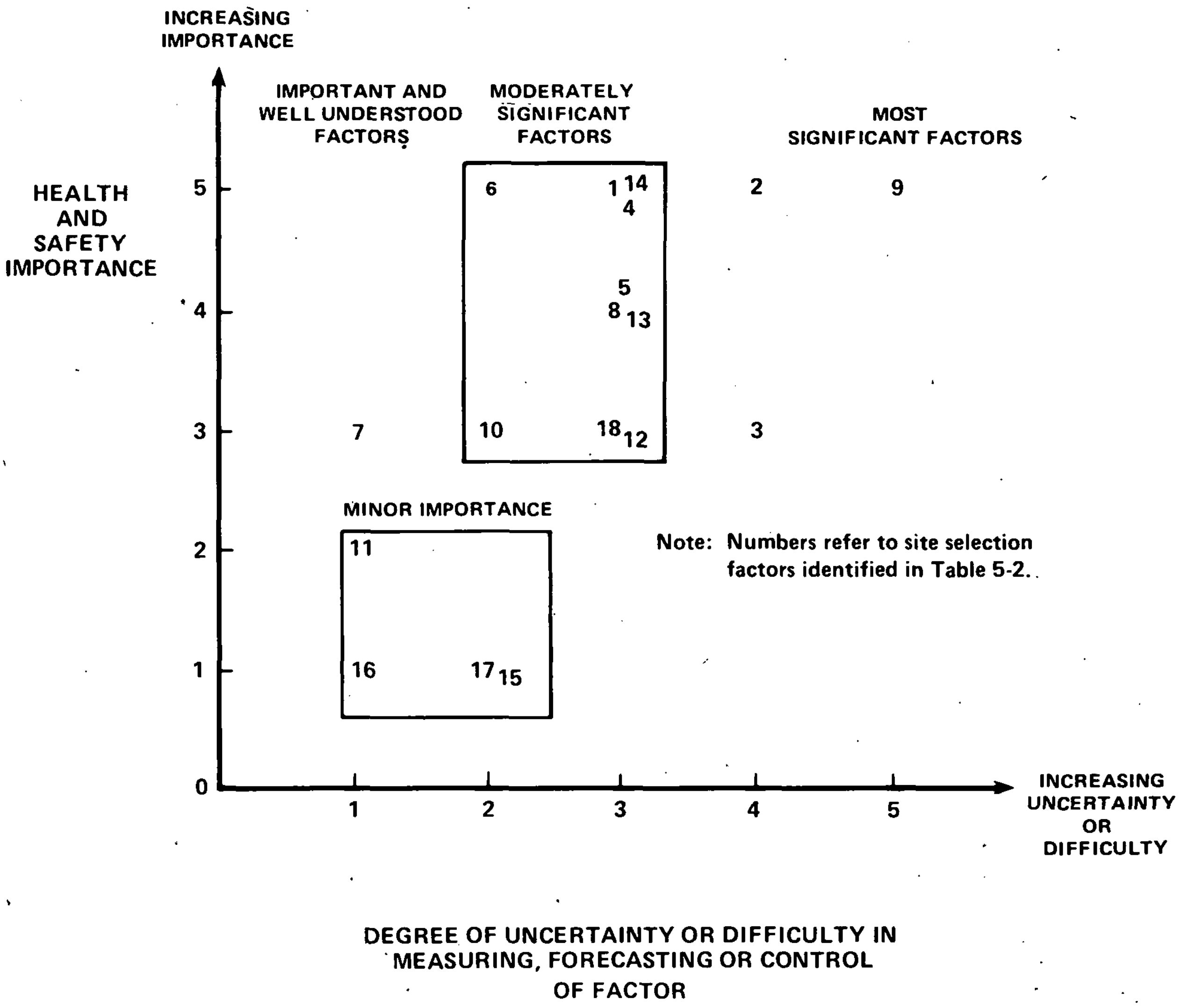


FIGURE 5-3 POTENTIAL SIGNIFICANCE OF SITE SELECTION FACTORS RELATIVE TO HEALTH AND SAFETY

of course, the GCDF is constructed in a western arid site in easily excavated unconsolidated soil. Also, the physical and chemical characteristics of soil, in addition to being very difficult to measure, are extremely important along with soil depth in assessing the costs of excavation. Interestingly, the mineralogical value of the land has a strong influence on future excavation probability and therefore, while not known with certainty, on the potential for inadvertent human exposure.

Figure 5-3 compares the ranking of the factors relative to the two attributes--health and safety importance and the degree of difficulty in measuring, forecasting, or controlling the impact of the factors. The right-hand column in Table 5-6 summarizes the ranking of the factors shown in Figure 5-3. The factors are listed in order of decreasing significance. The factors (represented by the identity numbers from Table 5-2) fall into two clusters, identified by the second and fourth group headings under "Figure 5-3 Factor Groupings" of Table 5-6. These two clusters are characterized according to the potential significance of the factors on health and safety as follows:

- The first cluster, shown in the upper middle of Figure 5-3, represents those factors which are considered important to health and safety (importance ranking of 3, 4, or 5) and have a moderate uncertainty ranking of 2 or 3. They represent both environmental and geotechnical factors which may be somewhat difficult to measure or forecast. They are, in order of decreasing significance, potential mineralogical value, distance between the waste and the aquifer, subsurface hydrology, surface hydrology, meteorology and climatology, probable plant or animal intrusion, tectonic activity, location of waste generators, erosion, and the potential recreational value of land.

- The factors in the second cluster are in the minor importance group and are identical to the set of factors in the minor importance group of Figure 5-2.

Two other groups of factors in Figure 5-3 which do not fall into definable clusters are described as follows:

- Demography, located by itself in the upper right corner of Figure 5-3, is considered the most important with regard to health and safety (i.e., has an importance ranking of 5) and is also quite difficult to forecast or control (i.e., has an uncertainty factor of 5).

- Also, the physical and chemical characteristics of the geologic strata are very difficult to determine and, together with the waste characteristics, have a significant impact on the migration and retention of nuclides within the ground and therefore on the health and safety of the public. For example, little specific data exists on such waste characteristics as leachability, chemical makeup, radionuclide content, etc., which greatly influence nuclide migration. Likewise, the technology needed for determining how the geologic strata will respond to migrating leachate is very poorly developed or is almost totally empirical.

- Soil cover depth, shown in the upper left of Figure 5-3, is one factor that is important to health and safety but can be accurately determined and controlled using the methodology in Appendix A.

Figures 5-2 and 5-3 and the groups summarized in Table 5-6 illustrate that demography, of all the factors, is considered to be the most important in affecting the health and safety of the public and the cost of waste disposal. Demography is also the most difficult to forecast or control because it involves the uncertainty of social activity and change. Population shifts cannot be anticipated over the 100 to 10,000 year period that the waste can be expected to remain hazardous.

The factors in the upper middle cluster of Figure 5-3 are also considered significant with regard to their impact on health and safety (i.e., distance between waste and aquifer, potential mineralogical value, subsurface hydrology, erosion, etc.) but are not as significant as demography because they are more easily measured. They represent a composite of important environmental, geotechnical, and sociopolitical considerations, which may vary widely among different sites. Because certain of these considerations can be directly affected by variations or changes in such factors as tectonic activity and meteorology and climatology, which themselves are moderately difficult to forecast, there is a moderate degree of uncertainty regarding the ability to forecast and control the future impact of changes in these factors affected as well. In addition to the factors meteorology and climatology, certain of the factors such as plant and animal intrusion are moderately difficult to measure and forecast even with a substantial effort. However, the uncertainties of impacts of changes in climate or tectonic (earthquake) activity can be reduced using analysis to predict and bound the long-term impact of changes in these factors.

Good engineering judgement in the design of the facility and in the selection of the site may be the best method to minimize the possible undesirable impacts of geotechnical and environmental factors, even though specific parameters cannot be accurately measured or controlled. If, for example, the distance between the waste and aquifer is anticipated to be large, the health impact of waste burial is expected to be small. Similarly, burying the waste at sufficient depth (i.e., utilizing GCD) can essentially eliminate plant and animal intrusion. Locating the facility out of the way of the flood wave will likely reduce the uncertainty of erosion due to flash flooding. Also, where the site is located in a suitably determined arid environment with little mineralogical value or history of tectonic activity, the physical and chemical characteristics of the strata may be more homogeneous and thus more favorable, and the impact of current or potential meteorology (precipitation) and the uncertainty of tectonic activity can be minimized. Finally, selection of an arid site is likely to reduce the probability of unfavorable demographic shifts, at least for the foreseeable future.

It should be recognized that those factors rated least significant (potential archeological and recreational value of land) have been evaluated in terms of the three attributes described at the beginning of this section. These attributes focus heavily on health and safety and cost aspects rather than sociopolitical considerations. Had a different set of attributes been chosen for the evaluation, the parameters may have been assigned different degrees of importance.

6. CRITERIA AND STANDARDS FOR GREATER CONFINEMENT DISPOSAL

Greater confinement disposal in most aspects is not particularly different than shallow land burial. The requirements for most operating equipment, support facilities, personnel, site security, transportation, packaging, radiation protection, monitoring, and health and safety are essentially the same for the two concepts. Some differences in operating equipment may be necessary because of the deeper burial. Most of these differences, however, can be considered as design parameters unique to a specific site.

The recommended generic criteria listed below have been divided into seven categories which are further subdivided into more specific criteria. Each criterion is followed by a corresponding standard or standards and a discussion.

6.1 RADIATION EXPOSURE PROTECTION

There are two separate groups of people who must be protected from the radiation associated with the management of the low-level waste; namely, the radiation workers at the disposal site and the general public residing outside of the site boundaries. Radiation doses to operating personnel shall be kept as low as reasonably achievable.

6.1.1 Operating Personnel

Criterion: Operating personnel will not be subjected to radiation at levels for which statistically discernible adverse effects are anticipated.

Standard: Radiation doses to operating personnel shall in no event be allowed to exceed the limits in the Code of Federal Regulations, Title 10, Part 20.

Discussion: The nuclear industry has over 35 years of experience in controlling radiation exposures to radiation workers. There is nothing unique in the GCD concept that will cause excessive exposures. Continued use of good radiation safety procedures at the work place as practiced at other disposal sites will assure compliance with these criteria.

Current limits for occupational exposure are set at 5 rem per year whole body. However, it is the general practice of the nuclear industry to limit occupational exposure somewhat below this level.

6.1.2 General Public

Criterion: The general public shall not be exposed to radiation doses above levels for which statistically discernible effects are considered acceptable and safe.

Standard: Radiation doses to the general public shall not exceed the guideline doses listed in the ICRP publication No. 26, adopted in January 1977, or such other guidelines as may be subsequently published to replace the ICRP guidelines.

Discussion: The general public radiation dose guideline as listed in the ICRP publication No. 26, which is consistent with NRC and EPA guidelines, gives 500 mrem/yr as a maximum allowable (worst case) limit for a few individuals (10's of individuals). The averaged individual dose for a large population is limited to 170 mrem/yr (Reference 11). The guidelines proposed for greater confinement, which represent a conservative approach, allow a whole body exposure of 3 mrem/year or 10 mrem/yr to any organ from routine releases to personnel in an unrestricted area. The allowable concentration limits (listed later in this section) for waste disposed at greater depths at arid sites, were calculated using worst case assumptions for both the expected arid and limiting case humid site conditions, i.e. those assumptions such as drilling a well beside the waste disposal site, that would result in a maximum individual dose of 500 mrem/yr. When site specific conditions are applied accounting for dilution in the aquifer, the atmosphere, and considering that only a small fraction of all the food ingested by a person living on the arid site could be grown above the disposal site, the normal expected or "routine" releases from a site would be well within the 3 mrem/yr guideline.

6.2 CHARACTERIZATION OF WASTE

The physical and chemical makeup of low-level waste (LLW) varies over such a wide range that it is important to characterize the LLW that is buried in the GCDF according to the properties that are significant to long-term disposal. For shipments of waste having radioactivity in excess of a reference low-level waste permissible concentration, it may be necessary to perform nuclide specific analyses for individual shipments. However for most shipments of waste, having radioactivity below a reference low-level waste concentration, it is impractical and probably unnecessary to analyze each shipment of waste to determine the isotopic distribution. However, it should be possible to periodially analyze a sample of the contaminating material that would most probably be found in waste from a specific source. If the waste manager is supplied with specific nuclide distribution data from each waste generator, he will be able to maintain an estimated inventory of each nuclide disposed. This will be possible even though individual waste shipments may only be labeled as x curies of mixed fission products from source y. This approach is applicable for DOE waste because its waste comes from a limited number of generators. The following are criteria considered important for LLW characterization.

6.2.1 Waste Description

Criterion: Waste accepted for disposal shall be identified as to its source, physical characteristics and general chemical makeup.

Standard: All high-specific-activity or non-low-specific-activity (HSA or non-LSA) waste containers and waste containing long-lived isotopes, including TRU wastes, shall be marked with a durable label describing the contained waste, the date it was packaged, the generator of the waste, and any identification number related to accompanying paperwork which is compatible with a computer data base and which describes associated hazards, radionuclides, etc.

Discussion: Low-level wastes are usually identified according to properties important to handling and transportation. The characteristics normally identified are the type and amount of the predominant radiation, physical state, combustibility, etc. This kind of characterization is useful during handling and transportation but it is not adequate for determining safe disposal requirements.

6.2.2 Documentation

Criterion: Accurate documentation of the curie content, source, nature and location of the waste shall be recorded at the time of disposal and maintained for whatever period of time is deemed to be pertinent for institutional control of the site.

Standard: A data processing system shall be established to record for each waste shipment, as a minimum, all data pertinent to source, type of waste, physical and chemical characteristics, and radioactivity. Records shall be maintained as long as institutional control of the site is deemed necessary.

Discussion: A record of the nature and origin of the LLW disposed of must be established, maintained, and made accessible to the general public or its representatives in order to assure the public that prudent procedures are being followed. This system will be part of the locator system used at the disposal facility. At a minimum, it will include information on the type of waste (isotopic distribution, physical, chemical and biological characteristics), the source of the waste, the waste generator and destination. Such a system will provide data necessary for proper handling and transportation under normal conditions and for appropriate response in case of an accident. Good documentation is required to make certain that all of the waste generated is promptly accounted for and that waste is not shipped to facilities which are not appropriate for its disposal.

6.2.3 Waste Container

Criterion: The waste container shall be adequate to maintain its integrity during transportation, handling, and stacking at the disposal site, and, for certain waste types, for a sufficient period after disposal (i.e. 100 years) to permit decay of the waste to levels that would not impose a public hazard if the container were breached after this time. (The lifetime of the container may be less than 100 years if the integrity of the waste disposal cell is designed to be maintained for 100 years).

Standard: A waste container shall be capable of supporting five times its own maximum loaded weight applied uniformly in the direction in which it will normally be stacked, or 141 kg/m^2 (2 psi), multiplied by the maximum horizontal cross section of the container, whichever is greater. For certain types of waste (e.g., tritium) the containers should be designed with a reasonable period of integrity (e.g. 100 years) to permit decay to nonhazardous levels by the end of the control period.

Discussion: The waste container is important during handling and transportation since it provides the primary protection during both normal and accident conditions.

Waste package requirements in the past have been based on the need to provide containment and radiation shielding during handling and transportation. The same containment and shielding are necessary during the emplacement of waste at a disposal facility. An unplanned release of contamination at a disposal site could greatly increase the radiation exposure of the workers and may render the monitoring system ineffective. Failure of the container before the waste has been disposed cannot be tolerated.

The performance requirements of waste containers after disposal are difficult to define. The analysis of allowable waste concentrations provided in Appendix A assumes that a container maintains its integrity for at least 100 years. The assumed integrity can have a material effect on potential impacts from tritium (half-life of 12.3 yr); however, the same package would have very little effect on Carbon-14 (half-life of 5,730 yr). Generally, in evaluating the potential for migration of the nuclides from the disposal site, the integrity of the container is disregarded once the 100-year period is past and only the effects of the natural barriers are considered. For most types of waste, burial at depths greater than 30 meters should be sufficient natural confinement to prevent a health hazard and there may be no need of a high-integrity container.

6.2.4 Volume Reduction

Criterion: The volume of the waste material shall be minimized, consistent with contemporary engineering and economic factors.

Standard: Compactible or combustible waste shall be reduced in volume to the extent practical through the use of incinerators or compaction equipment.

Discussion: Reducing the volume of waste can be useful in decreasing transportation impacts, reducing disposal volume requirements and, for some waste, providing a more stable waste form. Volume reduction often improves the chemical stability of the wastes. In the case of biological wastes, the biological hazard may also be reduced.

Volume reduction results in a more dense waste package, which facilitates the rapid consolidation of the facility. At the same time there can be occupational hazards involved with the volume reduction process and minor amounts of toxic effluents may result. One item of particular concern is that volume reduction concentrates the specific radioactivity of the waste. Volume reduction will increase the nuclide concentration in the waste. Care must be taken to ensure that this does not cause disposal concentration limitations to be exceeded.

6.2.5 Waste Form

Criterion: The physical state of the waste shall be a solid form.

Standard: Waste shall be in a dry solid form containing not more than 0.5 percent by volume or 3.8 liters (1 gallon) of free neutralized liquid per container, whichever is less. Liquids shall be immobilized by absorbtion in a dry, free-standing, homogeneous, monolithic matrix which is not readily dispersible, friable, or soluble.

Standard: Liquids may be accepted for disposal provided there is no other practical means to immobilize or solidify the liquid and specific DOE permission is granted, and provided reasonable assurance can be given that the liquid will be completely contained in the disposal facility throughout the time the liquid remains a radiologic hazard (e.g., reasonable assurance may be demonstrated by use of high-integrity containers).

Standard: The waste form shall not be liable to cause fires through friction, absorption of moisture, spontaneous chemical changes, or retained heat from manufacturing or processing, or when ignited, burn so vigorously and persistently as to create a hazard during handling, storage, and disposal operations.

Standard: The waste form shall not contain untreated oxidizing material, including chlorates, permanganates, inorganic peroxide, nitro-carbo-nitrates, nitrates, or any other material readily yielding oxygen in sufficient quantity to stimulate combustion.

Standard: Reactive LLW, for which there is no practicable way to reduce reactivity, may be accepted for greater confinement disposal if isolated in boreholes subject to specific DOE permission. Reactive waste in boreholes may be considered isolated if the depth of burial and borehole interspacing is greater than 10 meters or the greater of the distance required to adequately absorb the shock of detonation of twice the material without affecting nearby holes. Such materials may include waste which is as follows:

- Normally unstable and easily undergoes rapid chemical change without detonating; reacts rapidly with water or forms potentially explosive mixtures with water; generates or decomposes to form sufficient explosive or toxic gases, vapors, or fumes to be a hazard; or is a cyanide- or sulfide-bearing waste which can generate toxic gases, vapors, or fumes when exposed to mild acidic or basic conditions.
- Readily capable of detonation or of explosive decomposition or reaction at normal temperatures and pressures, or which reacts explosively with water.
- An explosive; i.e., any chemical compound, mixture, or device, the primary or common purpose of which is to function by explosion with substantially instantaneous release of gas and heat.

Discussion: No waste containing free liquids should be emplaced in the waste disposal site. Before liquid wastes are packaged, they should be rendered solid by adsorption on an appropriate medium or the liquid extracted through an ion exchange column or an evaporator. If aqueous liquid is adsorbed, it is usually preferable to convert it to a hydrate such as cement so that the water becomes chemically bonded to the solid.

The above standards are adopted from Reference 12.

6.2.6 Waste Concentration

Criteria: The average concentration of radioactive nuclides in the LLW disposed in a GCDF at a generic arid site shall be low enough that releases to the biosphere will be within acceptable limits.

Standard: The concentrations of various nuclides shall not exceed the limiting case area concentration limits shown in column 1 of Table 6-1. The area concentration limits represents the amount or inventory (curies) of waste that can be disposed in a GCDF per unit area (square meters) of site dedicated for disposal. The allowable concentration limits calculated for arid site conditions (expected case) are shown for various nuclides in column 2 of Table 6-1 for comparison. Where isotopic concentration limits are not listed, the concentrations of the isotopes are unrestricted, provided the radiation and thermal emissions of the waste package are within acceptable limits. Wastes having concentration below those shown in column 3 of Table 6-1 should be considered for disposal at shallow land burial sites.

Discussion: Disposal of LLW in a GCDF at an arid site, with the use of a thicker cover, greatly reduces the credibility of most of the reclaimer-related exposure pathway scenarios that limit the concentration of most nuclides in waste disposed near the surface of the earth. The only exposure pathway that becomes shorter than it is with shallow land burial is the groundwater pathway. A limiting case was developed in Appendix A representing either a humid site or a "worst case" scenario at an arid site (depth from the surface to the aquifer excluding the thickness of the waste, equals 160 meters) where irrigation is initiated for farming or a significant change of climate has occurred. A disposal concentration limitation, based on the groundwater pathway and other plausible exposure pathways for the generic arid western disposal site, even under the limiting or "worst case" conditions is applicable only for the isotopes for which disposal concentration limits are given in column 1 of Table 6-1. For a more detailed description of the pathway analysis, see Appendix A.

The concentration limits given in Table 6-1 are based on a selected set of parameters representative of the expected conditions at an arid site and, for the limiting case, conditions at a humid site with a very deep aquifer. Allowable concentration limits for waste disposal at a particular site would depend on the site conditions, waste inventory, type of waste, form, container integrity, facility design, etc. Such concentrations could be determined using the methodology given in Appendix A. Note: The allowable area concentrations given are average concentrations. Higher concentrations in a few containers may be acceptable provided the average concentration of wastes disposed at the facility are not exceeded. This condition is met when the sum of the total quantity of each isotope in the waste divided by the respective ACL does not exceed the total surface area at the site available for disposal. An example calculation demonstrating the application of the concentration limits in determining the maximum inventory loading capacity of a waste disposal cell and disposal site is given in Appendix B.

TABLE 6-1

AREA CONCENTRATION DISPOSAL LIMITS FOR MOBILE NUCLIDES(a,b)

Nuclide	Humid Site(c) Greater Confinement (Limiting Case) Area Concentration Limits ACL(Ci/m^2)	Arid Site(d) Greater Confinement (Expected Case) Area Concentration Limits ACL(Ci/m^2)	Shallow Land Burial(e) Area Concentration Limits ACL(Ci/m^2)
H-3	940	6,500,000	460(g)
C-14	2.3	3.8	0.0024
Ni-59	3.7	240	(h)
Ni-63	220	24,000	(h)
Co-60	(f)	(f)	1900
Sr-90	36	5100	.020
Tc-99	1.1	1.1	0.10
I-129	0.0011	0.05	0.30(g)
Cs-135	16	690	(i)
Cs-137	12,000	13,000	1.3
Ra-226	0.011	6.3	(h)
Th-230	0.0099	0.38	(h)
U-234	14	310	(h)
U-235	0.4	9.3	0.03
U-238	(f)	(f)	0.03
Np-237	0.13	19	(i)
Pu-238	23,000	54,000	(i)
Pu-239	5.5	210	(i)
Pu-240	11	420	(i)
Pu-241	68,000	2,100,000	(i)
Pu-242	4.5	170	(i)
Am-241	2400	7,600	(i)
Am-243	1 4	51	(i)
Cm-242	2,100.000	(f)	(i)
Cm-244	2400	150,000	(i)
Unidentified LLW	330	2,900	---

(a) Based on Pathway Analysis developed in Appendix A.

(b) Application of ACL's discussed in Appendix B.

(c) Assumes for humid conditions: a vertical groundwater velocity of 5m/yr and dispersion of 100 m^2/yr.

(d) Assumes for arid conditions: a zero vertical groundwater velocity and dispersion of 0.1 m^2/yr.

(e) Shallow Land Burial Guidelines from Reference 12 and assuming 1 meter waste thickness.

(f) The calculated allowable area concentration limit, ACL, exceeds the specific radioactivity of the nuclide.

(g) Isotopes concentration limits exceed or may be incompatible with those calculated for this document.

(h) Isotope concentration limit is not listed in Reference 12.

(i) Isotope concentrations are limited to 10 nano Curies/gram under current guidelines (i.e. <0.02 Ci/m^2).

6.3 TRANSPORTATION AND HANDLING

With few exceptions, the nuclear waste will be generated some distance away from the disposal site. Transportation to the GCDF often will involve use of public highways and also will cross state boundaries. The Department of Transportation has issued numerous regulations governing the movement and control of radioactive materials.

6.3.1 Packaging for Transport on Public Roads or Railways

Criterion: The waste package, including any overpack container or shielding, shall be capable of maintaining its integrity through any credible transportation accident.

Standard: The waste container shall conform to the pertinent regulations of the Department of Transportation, the Nuclear Regulatory Commission, and any applicable laws of the state through which it may be transported.

Discussion: The packaging requirements for transportation and handling are generally more rigorous than the requirements for disposal. Transportation activities (e.g., stresses experienced by a waste package in transit) may far exceed those experienced in stacking at the disposal site. Reusable overpacks and tiedown equipment may be used to achieve the necessary integrity during transit. Such considerations are not unique to LLW, but apply to the transport of any hazardous material.

6.3.2 Packaging for Off-Loading and Stacking

Criterion: Waste containers shall be designed with adequate strength to maintain their integrity during normal off-loading and stacking operations.

Standard: All packaged LLW accepted for disposal shall at a minimum meet the water spray, free drop, compression, and penetration tests of 49 CFR 127.611 for Type A packages without deformation, loss or dispersal of the contents, or an increase in the maximum radiation levels recorded or calculated at the external surface of the package.

Discussion: The handling requirements for the GCDF are the same as those for shallow land burial. No unique handling situations are anticipated that would increase the packaging requirements above those that have traditionally been observed by good waste management practices.

6.3.3 Access Roads

Criterion: Adequate roads into and out of the disposal site shall be maintained to provide safe driving conditions and all weather access to the facilities.

Standard: Access roads will be improved to the quality necessary to support in all weather the size and weight of transport vehicles normally used for waste delivery. At a minimum, the road surface will be regularly graded, compacted gravel.

Discussion: Well maintained access roads are necessary to permit year-round operation of the GCDF. Above-ground accumulations of waste awaiting disposal must be avoided to prevent excessive radiation doses to workers and extra handling costs. In addition, the roads must be safe to reduce the probability of accidents and possible spillage of the radioactive waste.

6.3.4 Transport Mode

Criterion: Radioactive wastes shall be transported in a manner that will protect the public health and safety.

Standard: Wastes shall be transported to the disposal site by rail, common carrier, or equivalent ground transportation. Air transport of radioactive wastes will not be used.

Discussion: The transportation of LLW to a GCDF poses no restraints that have not previously existed for LLW transportation. The existing transport regulations for shipments of LLW to shallow land burial will continue to be observed.

The safety record for LLW transportation in the past has been very good. From the experience to date, there appears to be no need for special routing requirements for most LLW. However, good judgment should continue to be exercised to preserve the established record. This includes minimizing the transportation distance consistent with avoiding highly populated areas when practical.

6.3.5 Disposal Site Waste Handling

Criterion: Waste shall be off-loaded and emplaced in the disposal site in a manner that will minimize violating the integrity of the waste containers.

Standard: Material handling techniques and equipment of demonstrated reliability and safety shall be used to off-load and emplace waste in the disposal facility.

Discussion: Waste handling at burial grounds has passed through cycles of care in handling (Reference 13). There was a time when random dumping of waste followed by pushing it in place with a bulldozer was considered an acceptable practice. Today, waste is generally stacked in a relatively careful manner. Care should be exercised to preserve the integrity of the container until a soil covering has been applied over the emplaced waste.

6.3.6 Inspection of Waste Received

Criterion: Waste shall be inspected upon receipt to assure that the health and safety of the public and radiation workers are protected.

Standard: Waste containers shall be inspected, without jeopardizing the container integrity, upon arrival at a disposal facility for compliance with the following:

- External surface or contact radiation not exceeding 200 mrem/hr (If an overpack or shielding is used, this requirement applies to the outside of the overpack or shield)
- No evidence of free liquid
- Container design appropriate for burial
- Container integrity
- Approved handling attachments
- Approved container marking
- Documentation as described in Section 6.2.2
- Waste conforms to label and documentation

Discussion: Containers that fail to pass the receiving inspection standards are also unsafe to return to the sender (waste generator) for corrective action. Rework of containers will generally have to be performed at the site by the disposal facility operator. Rework is costly and time consuming, and the disposal facility is not normally equipped with appropriate facilities to handle extensive rework. It also increases the possibility of contamination of the disposal site monitoring system. It is imperative therefore that waste generators comply with the applicable packaging and shipping requirements to assure that wastes will arrive at their destination in an acceptable manner. This places the main burden of inspection on the generator or shipper of waste and not on the receiver (GCDF).

6.4 SITE SELECTION

Many factors must be considered when selecting a site for radioactive waste disposal. The present attitude toward anything associated with nuclear energy seems to be one of fear and mistrust. Many people who profess to be in favor of nuclear power will still resist locating a nuclear facility in their vicinity. The sociological factor alone will dictate that any new facility must be located in an area as remote from large population centers as possible.

The determination that a site is suitable for a given waste disposal facility is based to a very large extent on the characterization of that site through modeling. Information specific to a given site is required for that modeling. The type and amount of information depends on the nature of the site, the proposed disposal method, the type of waste to be disposed, and the degree of confidence being sought. The information required for site characterization may also serve as part of the baseline data for the monitoring program.

At a minimum, the factors presented in the following sections must be evaluated in selecting a disposal site.

6.4.1 Subsurface Hydrology

Criterion: Hydrological factors shall be such that reasonable modeling calculations of nuclide migration show that any release of nuclides via the groundwater pathway shall not exceed acceptable limits.

Standard: The waste disposal site shall be located in an area where the hydrology and stratigraphy are such that the movement of water or moisture through unsaturated zones can be measured or calculated, and which will provide for several hundred years of residence time for radionuclides migrating to a surface water body or to a supply aquifer that might be tapped by water wells.

Standard: The facility shall be located so that the depth or location of any water-bearing formation in the area of the disposal facility site, whether perennial or otherwise, is such that groundwater intrusion into the waste placed into the disposal facility is minimal.

Standard: The facility shall not be located in the recharge area of a sole source aquifer designated pursuant to Section 1424(e) of the Safe Drinking Water Act (Public Law 93-523).

Discussion: Water leaching of radionuclides from the waste and subsequent movement of the nuclides with the unsaturated zone groundwater is considered to be a major pathway by which man can be exposed to radioactivity. Placing waste deeper in the ground than in shallow land burial reduces the distance the nuclides must travel in order to contaminate the aquifer below the disposal site. At some sites, this difference would be inconsequential. At others, it could be great.

Migration of radionuclides via the groundwater pathway is highly sensitive to the characteristics of the particular site. The potential exposures from the groundwater pathway are affected by several factors including physical and chemical properties of the waste, engineered barriers of the disposal facility, groundwater chemistry, the retardation potential of the soil, groundwater travel time to point of utilization by man, animals or crops, and the fraction of groundwater actually consumed or used in food production. Potential variations in hydrologic conditions should also be considered. Variations in hydrology could occur as the result of climate changes, construction of reservoirs and irrigation systems, and other natural or man-induced changes in groundwater systems.

It is difficult to make accurate, predictive calculations of nuclide migration in complicated hydrologic systems, particularly for those systems with unsaturated zones or fractured zones. Even simple hydrologic system calculations are normally limited to those describing the conservative or "worst case". The "worst case" as used in this document and developed in Appendix A is represented by a set of limiting case site conditions analogous to the conditions that would exist at a humid (eastern) site. The "worst case" scenario at an arid western site assumes initiation of irrigation farming directly over the burial site. For some sites such a scenario, while possible, is not particularly probable because of the depth to the aquifer, the distance from population centers, and the general undesirability of the soil.

Because of the inability to perform realistic predictive calculations of complicated patterns of groundwater migration, attempting to identify the "best" site based on hydrologic considerations may not be a sound approach to site selection. Emphasizing the degree of confidence that can be obtained, through selection of sites that can be accurately modeled, may be preferable.

6.4.2 Surface Hydrology

Criterion: Surface hydrological factors shall be such that the facility shall not be subject to periodic flooding or excessive water erosion.

Standard: No part of the facility shall be located in a 500-year floodplain or regulatory floodway.

Standard: The facility where the LLW is emplaced shall be sited so that the natural grade elevation of the facility surface is above that of the calculated water level resulting from floods, dam failures, or any other credible natural or man-produced event which could inundate and compromise the integrity of the disposal facility.

Standard: The facility shall be located in an area where surface water due to precipitation drains freely and does not collect or pond on the site surface, nor saturate the surface of the land, to the extent that such actions may cause an increase in potential LLW migration from the facility.

Discussion: The above standards were adopted from Reference 12. The surface features of a potential GCDF must be carefully considered and engineering changes made if necessary to assure that flooding of the site will not occur. This is especially important during the time that the facility is open. Such a flood could result in the waste being washed out of the facility and spread over a considerable area.

The GCDF, having a much greater depth than a SLB pit, if flooded, likely would be out of operation for several months while the water was drying or seeping into the ground, even if no contamination were released.

The proximity of any surface body of water that might become contaminated through an unplanned release of radioactive contamination must be carefully considered in selecting a site for a new GCDF.

6.4.3 Geology

Criterion: A waste disposal facility shall not be located in an area whose geological features preclude the reasonable prediction of nuclide migration in the strata surrounding the waste facility.

Standard: A waste disposal facility shall not be located in an area where the underlying geological strata does not provide long-term residence time for migrating radionuclides.

Standard: The facility shall not be located in an area where surface geologic processes such as mass wasting, erosion, slumping, landsliding, weathering, or glaciation could significantly enhance LLW transport from the facility.

Standard: The facility site shall be free of solution features, unseated faults, highly fractured bedrock, or formations containing sand lens, breccia pipes, or other permeable anomalies through which radionuclides could freely migrate into a public water supply.

Standard: The disposal facility shall not contain capable faults, nor be located near enough to a capable fault so that the overall rate of LLW migration could increase as a result of seismic activity.

Discussion: The last three standards listed were adopted from Reference 12. Highly fractured rock strata between the buried waste and an aquifer cannot be analyzed for nuclide migration. Such a formation could provide a direct channel for the nuclides from the waste to the aquifer and should be avoided. Similarly, a highly porous alluvial gravel may have very little retention for the nuclides and would also make an unsatisfactory disposal medium.

6.4.4 Weather

Criterion: The climatology of the waste disposal site shall be sufficiently moderate that waste disposal operations can be performed in all seasons of the year.

Standard: The records of the U.S. Weather Service for the disposal site shall indicate that on an average a minimum of 200 working days per year are available for waste disposal operations where inclement weather would not prevent continuing operation.

Discussion: Some compensation for inclement weather can be made. For example, an air support building can be installed over a disposal site to provide weather protection to the workers and the waste until it can be covered with soil. However, extended harsh weather patterns should be avoided. This includes areas with a history of frequent heavy thundershowers, high winds, severe snowstorms or extended periods when the ground is frozen to great depths. Such weather conditions severely limit waste management activities and could result in costly delays in disposing of the waste.

After the site is closed, the weather patterns on the surface would have very little influence on the waste as long as excessive moisture does not enter the site.

6.4.5 Erosion

Criterion: The waste disposal facility shall be located in an area where no excessive erosion is predicted.

Standard: The site surface area shall have a surface gradient of less than 8 percent and shall not be located directly downgradient from any major canyon or arroyo where flash flooding is likely to occur (Reference 12).

Discussion: The potential for erosion is highly site specific. Erosion can reduce the depth of cover over the waste and the ability of the disposal site to isolate the waste. It may also uncover the waste and increase human exposure to it.

Changes in the surface hydrology of the site as a result of climatic changes and human activities should be considered. For example, the area rainfall might increase, or changes in human activities could bring about adverse erosion patterns. Vegetation and engineered features should not be relied upon for controlling erosion for long periods of time. Disposal sites should be located in areas in which positive deposition or no significant erosion are anticipated.

6.4.6 Tectonic Activity

Criterion: A waste disposal site shall not be located in an area exhibiting evidence of recent major earthquake, volcanism, or geothermal activity.

Standard: The disposal facility shall not be located in an area having a peak horizontal ground acceleration of greater than 0.25 g with a recurrence interval of less than 500 years. (Note: A 500-year recurrence interval is equivalent to a 90 percent probability that the ground acceleration will not be exceeded in 50 years.)

Standard: The disposal facility shall not be located in an area exhibiting evidence of recent (historic times) volcanic activity.

Discussion: The first standard was adopted from Reference 12. All tectonic activity near a disposal site would not necessarily be detrimental. For example, a lava flow from a long surface fissure could leave a thick deposit of weather-resistant basalt over the surface of the disposal site. Such lava flows are typical of the deposition of most of the basalt strata now found on the Hanford, Washington Site and on the INEL Site in Idaho. However, the inability of geologists to predict this type of eruption would make it too nebulous to rely on. A violent volcanic eruption could scatter the waste over a great area. It is simpler to avoid areas of active volcanism.

Similarly, earthquake activity could work to either expose the waste or perhaps cover it more deeply. The uncertainty would dictate choosing an area with a low earthquake probability.

Geothermal water activity near the surface is an indication of complex hydrologic activities beneath the surface. Complex hydrology near a GCDF was rejected in Section 6.4.1 for other reasons.

6.4.7 Archeological Considerations

Criterion: A waste disposal facility shall not be located in an area that would cause destruction or loss of sites of historical or archeological importance.

Standard: An archeological survey of the proposed site area shall be made to assure that no important archeological material will be disturbed when the site is opened.

Discussion: For all new federal construction projects, the Historic Preservation Act mandates the determination of potential effects on cultural resources and the preservation of sites in situ or the preservation of historical and archeological data that might be irretrievably lost.

An archeological survey must be made of a candidate disposal site to assure that important archeological material would not be disturbed. Potential effects are not limited to the localities directly modified by the project, but may also include ancillary features such as access roads, power lines or construction crew camps.

6.4.8 Recreational Considerations

Criterion: The recreational activities of the general public will not be significantly affected by radioactive waste disposal operations.

Standard: Land having a high potential for recreational activities shall not be used for waste disposal.

Discussion: This is a very subjective consideration. In many areas such as southern California, the deserts are becoming increasingly popular for recreational activities. A site used for greater confinement disposal could possibly be reopened for surface activities after waste disposal is complete. This factor would need to be considered in any site selection.

The potential for future recreational activities is among the reasons for using greater confinement disposal for low-level waste. By disposing of the waste deeper in the ground than is currently the practice with shallow land burial, the chances for the waste to be disturbed by an inadvertent reclaimer are greatly reduced. Consequently, the surface area could be reopened for recreational activities within a relatively short time after the disposal of waste was terminated.

6.4.9 Natural Resources

Criterion: Future generations shall not be penalized nor deprived of the recovery of natural resources as a result of present-day waste disposal practices.

Standard: The waste disposal site shall not be located in an area known to contain resources whose recovery would pose a significant risk to future generations.

Discussion: A mineralogical survey of any proposed site should be made and evaluated. Arid desert sites may be underlain with deposits of such minerals as potash, borates, salt, coal or oil. Recovery of shallow deposits would be severely restricted by the presence of a radioactive waste burial ground. However, deeper mining may be possible without disturbing the waste.

The term "resources" should be used in the broad sense to include agricultural land, groundwater, mineral deposit and potential economic use of the land.

6.4.10 Flora and Fauna Impacts

Criterion: The waste disposal site shall not be placed in an area where it will pose a significant threat to any endangered species of flora or fauna.

Standard: The facility shall not be located so as to be likely to jeopardize the continued existence of endangered and threatened species as listed pursuant to the Endangered Species Act of 1973 (16 U.S.C. 1530, et seq.) in 50 CFR; nor result in the destruction or adverse modification of their critical habitat as contained in 50 CFR Part 17, Subpart F: Critical Habitat, 1760, et seq.

Discussion: The standard is adopted from Reference 12. The establishment of an area where human access is restricted in many cases will enhance the growth of most flora and fauna. However, it must be determined if the disposal site lies on a migratory route for such animals as deer or antelope. The interruption of migratory routes during facility operation could have far-reaching effects on animal populations a considerable distance from the actual site.

The area of a GCDF is probably too small to have any lasting effect on either plant or animal communities, but this factor should be examined for any potential waste burial site.

6.5 ENGINEERING

Factors that affect the performance of a GCDF, but which are under the control of the facility operator, are grouped together as engineering criteria. These items are discussed below.

6.5.1 Monitoring

Criterion: The public health and safety shall be protected from any adverse effects that may be caused by the waste disposal facility.

Standard: A careful monitoring program shall be established to assure that the buried wastes are being contained in the disposal facility as required to protect the public health and safety.

Discussion: The primary purpose of monitoring a disposal facility is to determine how well the disposal facility is performing.

A radioactive waste disposal facility monitoring system should include the following considerations:

- A monitoring system should gather data to determine the migration of hazardous materials and permit analysis of the chemical toxicity as well as the radiological hazards of the wastes.

- The proximity of nuclear reactors or fuel reprocessing plants whose radioactive releases could contaminate the disposal facility monitoring system should be considered.

- Baseline monitoring data should be obtained before operations begin and before any possible contamination of the site occurs.
- Radioactive releases from auxiliary operations such as waste repackaging may contaminate the monitoring system and be mistaken for releases from the disposal system. Any side operations must be conducted in adequate facilities far from the site to avoid even small releases of radioactivity.
- The monitoring system should measure data pertinent to analyzing migration of nuclides through the ground. Experiments should also investigate uptake by vegetation and animals.
- The monitoring system should measure changes in site characteristics which have the potential to impact the long-term performance of the site (e.g., changes in site hydrology or erosion rates).
- Monitoring should be provided to alert facility operators and record the occurrence of an unexpected operational release.
- The monitoring system should be simple, reliable and economical so that it will not place an unnecessary burden on future generations.
- Monitoring system requirements need to be identified in the earliest stages of the development of a disposal facility.

6.5.2 Disposal Depth

Criterion: Sufficient cover material will be placed over the waste to limit plant roots, burrowing animals or inadvertent human reclaimers from contacting the waste and bringing any significant contamination to the surface, and to minimize the potential cumulative impacts to man by plausible exposure pathways.

Standard: Waste shall be deposited in the earth at sufficient depth that a minimum of 10 meters of regolith cover or equivalent engineered barriers can be placed over the waste to prevent root and animal intrusion; an optimal cover depth of 30 meters is proposed to minimize the exposure to man from drinking well water drawn from an underground aquifer or consuming crops grown above the waste site. The 30-meter depth is based on an assumed waste thickness of 10 meters, such that the average or optimal waste depth is 35 meters and the assumed depth between the surface and aquifer is 170 meters at a generic arid western site. Sufficient material shall be added and compacted above the waste to restore the surface to grade level and original soil consistency.

Discussion: The typical thickness of cover used with shallow land burial is about 1 to 3 meters. This relatively thin cover requires active maintenance for many years as the wastes compact in the pit and the surface subsides. It is desirable to have vegetation growing over the pit to prevent erosion but deep-rooted plants must be excluded to prevent uptake of radionuclides. Disposal of wastes at greater depths is intended to significantly reduce the effects of surface phenomena and the probability of intrusion by plants or animals. The methodology used to determine optimum depth at a typical arid western site is given in Appendix A.

For disposal of certain types of high specific activity wastes, including for example Co-60, Cs-137 or Sr-90, a period of administrative control may be required to allow decay of the waste to reduce the potential hazard to a human who may occupy the site to acceptable levels. Because the waste is still in relatively close proximity to the surface, even at 30 meters, greater confinement disposal is not intended to eliminate completely the reclaimer scenario, but rather to reduce the probability of its occurrence and its risk to man to a level of acceptability.

How deep the waste can be buried economically depends greatly on the characteristics of the individual sites. Where the unconsolidated material is deep, such as at the Nevada Test Site, a deep pit probably could be excavated at unit costs only slightly higher than those for shallow land burial. However, for some sites; e.g., the present INEL Radioactive Waste Management Complex (RWMC), basalt strata will be encountered at less than 10 meters in most places. Excavation of GCD pits at some sites may not be economically feasible.

Where the depth of unconsolidated material is sufficient to justify the establishment of a GCDF, the waste could be emplaced in layers with intermediate thin (~1 m) soil covers over each layer to facilitate stacking. In this manner, the total waste thickness could be from 10 to 20 m.

6.5.3 Buffer Zone

Criterion: No member of the public shall be exposed to radiation at levels for which adverse effects are anticipated, consistent with economic considerations.

Standard: A controlled access zone shall be maintained around the perimeter of a radioactive waste disposal site to prevent the inadvertent exposure to ionizing radiation of transient visitors to the area.

Discussion: Release of unplanned contamination to the area surrounding the disposal area should be guarded against. A buffer zone surrounding the disposal facility is required to assure that potential exposures to individuals are restricted to acceptable levels. The size of the buffer zone will depend on the facility design, site characteristics, type and amount of waste being disposed of, acceptable exposure levels and the degree of confidence desired. The size of the initial buffer zone should be determined through somewhat conservative water pathway modeling. As the results of the monitoring program provide better prediction of the actual site performance, the size of the buffer zone may be reduced. A procedure for calculating the required buffer zone or excluded utilization area surrounding a waste disposal cell or site is provided in Appendix B.

6.5.4 Stratified Disposal

Criterion: The inadvertent reclaimer shall be protected from receiving a high radiation dose on his initial contact with the top of the waste.

Standard: Whenever possible, radioactive waste shall be emplaced in the disposal pit in such a manner that containers holding high radiation level waste will be located at the lowest level in the pit.

Discussion: It has been observed (References 2 and 14) that about 90 percent of the activity in the waste from operating reactors is contained in about 5 percent of the volume of that waste. Low-level waste from government operations also follows approximately the same general distribution. Stratified disposal will minimize any possible future exposure to an inadvertent reclaimer who may excavate the waste by making the highest radiation waste the last he would encounter. The practice does place an extra burden on the operation of the disposal facility.

6.5.5 Engineered Barriers

Criterion: The facility shall be designed to enhance and improve the ability of the natural characteristics of the site to confine the waste after disposal, consistent with economic considerations.

Standard: The use of engineered barriers to nuclide migration will be employed in the GCDF only to the extent that their incremental cost can be justified by their projected lowering of exposure doses.

Discussion: Engineered barriers to waste migration can augment natural barriers and increase confidence in the ability of a disposal system to contain waste over the short term.

Barriers to waste migration can be classified as either naturally occurring or engineered. Natural barriers can be both the presence or the absence of certain features (e.g., the presence of high ion-exchange capacity or the absence of water). Natural barriers tend to be imperfect, but massive in extent. In general, natural barriers tend to retard migration of the waste, but at no time completely contain it. Barring such phenomena as excessive erosion or drastic changes in hydrogeology, natural barriers can remain effective over extremely long periods of time. Engineered barriers tend to have short usefulness but perform well over the short term. Examples of engineered barriers are the waste package and clay liners for the waste pits.

There are two major questions concerning the use of engineered barriers. First, there is little doubt that engineered barriers can effectively contain short-lived nuclides such as tritium. However, any disposal system should be capable of containing most short-lived waste relying on its natural barriers only. The question is, how effective will engineered barriers be in preventing the release of long-lived waste? Second, the effective containment of various types of low-level radioactive waste ensures that the waste remains concentrated, and thus, most hazardous to someone who may come in contact with it. The use of engineered barriers often means a reduction of risk off site and an increase in risk on site. In evaluating the need for engineered barriers, the potential risks both to the population (off site) and to individuals (on site) need to be considered.

6.6 GENERAL FACILITY REQUIREMENTS

There are several factors which must be considered when establishing a new waste disposal facility which are not directly concerned with the containment of the waste, but with social and political elements of the society in which we live. Criteria associated with these considerations are discussed below.

6.6.1 Ownership

Criterion: Radioactive waste shall be disposed where institutional control of the site can be maintained for as long as shall be deemed necessary to protect the public health and safety.

Standard: The location of a greater confinement disposal facility shall be on federally or state owned land.

Standard: Administrative control and security of the site shall be provided for a reasonable period after site closure (5 years minimum and 100 years maximum) to assure confidence that confinement of the waste at the site has been adequately demonstrated.

Discussion: It is presently the policy of the NRC and the DOE that all radioactive waste will be disposed on state or federally owned land. This policy was established because of the persistence of the hazard from the waste and the need to control the area while the waste remains hazardous.

Reasonable demonstration of confinement, while somewhat subjective, is indicated by the negative observation of impacts over a reasonable period of monitoring and observation. Long-term performance, while impossible to assure, can be suggested by the analytical results of predictive models.

With GCD, reasonable economic use of the land can be achieved much sooner than with shallow burial without disturbing the waste and without unreasonable risk to any individual. Certain restrictions on the land title may be all that is required.

At the present time, however, changes in federal regulations and policies would be required to release the site for future public use.

The above two standards are based on guidelines provided in the IRG Report to the President and in 10 CFR 61, respectively (References 8 and 12).

6.6.2 Demography

Criterion: No member of the public shall be exposed to radiation at levels for which adverse effects are anticipated.

Standard: A disposal site shall not be located near areas of high population density or where the future development of a high population density may be anticipated.

Discussion: There are no federal standards which define "high population density" or how far into the future demographic projections should be made. For this criterion "common sense" may be the only standard that can be applied. Anyone traveling through the West can quickly identify areas of low population density and high population density. The population density of some areas in the West is so low that any small town is high by comparison.

There are also areas where the availability of water will restrict future population growth, at least within the framework of present technology and economics.

For typical low-level waste most of the radioactivity will decay within a few hundred years. Therefore, demographic projections over a few hundred years should be adequate.

6.6.3 Land Use

Criterion: The amount of land committed to waste disposal shall not be permitted to grow to unreasonable dimensions.

Standard: The design and operation of the GCDF shall be guided by the principle of minimizing the amount of land area that is committed to nuclear waste disposal.

Discussion: The policy of minimizing land devoted to radioactive waste disposal grounds has been a guiding principle of DOE and NRC radioactive waste management for several years. It is recognized that any land dedicated to radioactive waste disposal may be unavailable for public enjoyment for several hundred years. Therefore, it is in the public interest to minimize the amount of land that is so committed, consistent with environmental and economic considerations.

6.6.4 Resource Commitment

Criterion: The GCDF shall require no significant commitment of resources by future generations.

Standard: After closure and stabilization of the GCDF, no further waste management activities are required to protect the general public from the disposed waste other than those limited to monitoring and administrative control.

Discussion: Design and site selection of a GCD facility should utilize predictive analytical models and field data, to verify the appropriateness of the site and identify any potential conditions which might compromise the long-term integrity of the facility.

Performance evaluation prediction prior to construction, appropriate design and construction practices, and re-analysis and verification of performance after the facility is closed should minimize the need for continued maintenance of the site or the requirement for further or continued resource commitments, such as "perpetual care funds." Even government-owned or defense-related sites should be designed in such a way as to not add to the tax burden of future generations.

6.7 ADMINISTRATIVE

Several other subject areas which are not unique to the GCDF are discussed briefly below. These criteria are treated in much greater detail in many other publications and are mentioned here only to indicate that the need for these criteria in connection with the GCDF is the same as for other nuclear facilities.

6.7.1 Surface Facilities

Criterion: Surface facilities will be removed from the site when their usefulness to the operation has ended.

Standard: Surface facilities needed for support of the disposal operation shall be designed and constructed in such a manner that they can readily be decontaminated and decommissioned when their usefulness is over.

Discussion: The buildings needed for offices, equipment storage, decontamination, lunch and change rooms, etc., to support the waste disposal operation will have a limited useful life. For a well-operated waste disposal facility there is very little potential of contaminating these buildings. However, if it is recognized at the conception of these facilities that eventually they will have to be decontaminated (if contaminated) and dismantled before the land can be released to the public, it should be possible to design them for easy decontamination and decommissioning. Provision for the possibility of an unplanned contamination release should always be made.

6.7.2 Personnel Training

Criterion: Operating personnel shall be trained and knowledgeable in radiological health and safety and in the use of the equipment and facilities needed for the waste disposal operation.

Standard: All personnel who are involved with the handling of radioactive materials will go through a radiological training course designed to familiarize them with the well-established operating practices for radiation workers. Mandatory refresher courses will be repeated periodically. All radiological training courses will be approved by DOE.

Discussion: These standard practices have made the nuclear industry one of the safest occupations for industrial workers in the United States.

In addition, all equipment operators will be trained in the operation of the equipment with which they are required to work.

6.7.3 Health Physics

Criterion: Waste management operations shall be monitored to assure potential radiological impacts are mitigated and exposures both to operators and to the general public are maintained well within levels for which no adverse effects are anticipated.

Standard: Technicians trained and knowledgeable of health physics procedures will be available to monitor waste management operations to assure compliance with radiation exposure requirements.

Standard: All operations involving radioactive material shall be under the direction of qualified health physics technicians.

Discussion: Waste disposal at deeper levels does not impose any new operational techniques on radioactive waste management. The present standards for personnel and exposure monitoring used in shallow land burial sites shall be continued for GCD.

6.7.4 Occupational Safety

Criterion: All employees shall be provided a safe working environment containing no unusual hazards to health and safety.

Standard: All routine operations will be performed in accordance with standard operating procedures that have been approved by the Health and Safety Department and that are prepared in accordance with the guidelines and standards published by OSHA and the National Safety Council.

Discussion: Employee safety shall be a major consideration in the construction and operation of the GCDF. The well-established safe work practices already in existence at nuclear facilities for handling and working with nuclear materials shall be continued. Guidelines and standards published by OSHA and the National Safety Council shall also be incorporated into the operating procedures to assure workman safety.

6.7.5 Site Security

Criterion: No unauthorized intrusion into a disposal site or unauthorized removal of waste material or equipment from a disposal site will be permitted.

Standard: The GCDF shall be provided with whatever equipment, structures, facilities and personnel are necessary to detect any attempted or actual intrusion of unauthorized persons onto the disposal site and to prevent the unauthorized removal of contaminated material or equipment.

Discussion: As part of the goal of protecting the health and safety of the general public, it is necessary to assure that any contaminated items, which may appear to be useful to an individual, are not allowed to leave the GCDF. Unacceptable and unknown exposures of many people could easily occur if the waste is not carefully controlled. Such a situation actually occurred a few years ago when workers at a commercial burial ground were salvaging contaminated tools and other items from the LLW and taking them home for their personal use. How much exposure resulted from this practice before it was stopped may never be known.

6.7.6 Fire Protection

Criterion: Provision shall be made to promptly extinguish any fire that may occur in the LLW or in the associated facilities.

Standard: The radiation workers shall be trained as a fire brigade and shall be equipped to extinguish small fires in their incipient stages. Special training in fighting fires in radioactive materials will be received by these workers. Provision shall also be made for alerting and calling on professional firefighting crews in the event a major fire should erupt that could not be handled by the fire brigade. Training for professional firefighters will be conducted on fighting fires in radioactive materials.

Standard: Citizens' band radios, telephones, automatic alarm systems, heat and smoke sensors shall be incorporated into the facility fire warning system design.

Discussion: Fire in radioactive waste will cause widespread distribution of the radioactive isotopes with smoke and airborne particulate matter. Although historically the incidence of fire in LLW has been very low, the potential will always exist until all combustible waste is processed through an incinerator before it is packaged for burial. Until such incinerators are available, adequate fire-fighting facilities and equipment must be available at the GCDF.

6.7.7 Personnel and Equipment Decontamination

Criterion: All personnel and equipment leaving the GCDF shall be free of any radioactive contamination and contamination within the facility shall be minimized.

Standard: All personnel leaving the disposal site will be monitored with appropriate radiation detection equipment. Any contamination found on an individual's clothing or person will be removed before the individual leaves the facility.

Standard: Equipment leaving the facility will be surveyed for surface contamination and appropriately decontaminated before release.

Standard: Permanently assigned equipment and facilities will be surveyed quarterly and decontaminated as appropriate.

Discussion: The spread of radioactive contamination is much easier to control at its source than it is to recover after it has been allowed to leave a nuclear facility. The practice of monitoring personnel and equipment leaving any nuclear facility has been enforced right from the beginning of the atomic energy program. The same controls used at other nuclear facilities must be incorporated for the GCDF.

6.7.8 Equipment and Facility Maintenance

Criterion: All equipment and facilities shall be maintained in a safe and operable condition.

Standard: All operating equipment and facilities will be set up on a regular, periodic preventive maintenance schedule. In addition, any defective equipment and facilities will be promptly repaired whenever the defect is discovered. No personnel will be required to operate unsafe equipment which may present a hazard to their personal safety or the safety of others.

Discussion: The value of an effective safety program has been well established in American industry. The maintenance of equipment in a safe operating condition is only a part of the safety program that should be established for a new nuclear facility. In addition, the regulations of OSHA applicable to workers' safety must be part of the GCDF operating plan.

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APPENDIX A

DETERMINATION OF NUCLIDE DISPOSAL CONCENTRATION LIMITS AND OPTIMAL BURIAL DEPTH

CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX A

DETERMINATION OF NUCLIDE DISPOSAL CONCENTRATION LIMITS AND OPTIMAL BURIAL DEPTH

Several different approaches have been used by various investigators to establish an upper waste concentration limit on disposal of low-level waste (LLW). Most of these limits are based on exposure to the general public through various postulated pathways. Several pathways to man that have been evaluated for shallow land burial (SLB) are essentially eliminated by deeper burial. Greater confinement disposal (GCD) places the waste below the depth where it will be directly disturbed by plant roots, burrowing animals, surface erosion and other in situ exposure scenarios. In addition, the increased soil cover associated with GCD is adequate to attenuate most of the gamma radiating waste.

Exposure pathways which must be examined for any disposal method include aquifer contamination and upgradient migration by molecular diffusion. Greater confinement disposal generally increases the risk of aquifer contamination at a given site because of the reduced distance from the disposal facility to the aquifer. In addition, because molecular diffusion follows chemical rather than hydraulic gradients, contamination may occur anywhere within the geosphere. Therefore, it is incumbent to examine both of these pathways in detail for an arid western GCDF and to determine at what optimal depth the exposure from nuclide migration in all directions can be minimized.

The purpose of this appendix is to determine the allowable waste concentration limits of nuclides and the optimal burial depth for LLW at a generic arid western GCDF site. The parameters assumed pertinent to a site characterization and migration analysis for the generic GCDF are given in Table A-1.

This appendix is divided into four sections:

- Section A.1 is a discussion of the various conditions and parameters at arid western sites which affect nuclide migration and the long-term performance of a disposal site.

- Section A.2 is a determination of the optimal depth of burial based on the plausible exposure pathways for typical low-level waste and a determination of the average allowable area disposal concentration limits for such waste and its nuclides.

- Section A.3 compares the calculated allowable area concentration limits and their waste disposal application for two extreme bounding cases: expected conditions at an arid site and the

TABLE A-1

PARAMETERS ASSOCIATED WITH NUCLIDE MIGRATION AT WASTE DISPOSAL SITES

Parameter	LASL	Hanford	NTS	INEL	Used in Calculations for Generic GCDF
Annual precipitation (cm)	40	16(a)	10(b)	22(c)	10
Thickness of vadose zone (m)	200 to 400	106(a)	213(d)	186(c)	170(e)
Soil type	weathered tuff	gravel, sand, silt(a)	alluvial tuff(f)	silt, clay(g)	sand, clay
Effective porosity of aquifer (%)	—	3 to 4(h)	2.3(d)	--	3.0
Aquifer velocity (m/yr)	—	1000(h)	52(f)	600(c)	700
Vadose zone porosity (%)	--	--	3-48(d)	--	10%
Vadose zone bulk density (g/cm^3)	--	--	--	--	1.6
Vertical unsaturated groundwater velocity (m/yr)	—	--	--	--	0(i)
Vertical saturated groundwater velocity (m/yr) - limiting case	--	--	--	--	5(i)
Diffusion coefficient in unsaturated zone (m^2/yr)	--	--	--	--	0.1(i)
Dispersivity (m)	--	--	--	--	20(i)
Optimal Burial Depth for GCDF (m)	NA	NA	NA	NA	35(j)

TABLE A-1 (Cont)

Parameter	LASL	Hanford	NTS	INEL	Used in Calculations for Generic GCDF
Depth to bottom of GCDF (m)	NA	NA	NA	NA	40(k)
Depth of soil cover (m)	NA	NA	NA	NA	30(k)
Assumed dimensions of GCDF site (or pit concept) assumed square (m)	NA	NA	NA	NA	60(k)
Assumed borehole dimensions					
Borehole diameter (m)	NA	NA	NA	NA	2(k)
Array spacing (m)	NA	NA	NA	NA	10(l)

(a) Reference A-1
(b) Reference A-2
(c) Reference A-3
(d) Reference A-4
(e) Includes 10 meter thickness of waste
(f) Reference A-5
(g) Reference A-6
(h) Reference A-7
(i) Appendix A assumption based on Reference A-8
(j) Calculated in Appendix A.2
(k) Appendix B parameter
(l) Appendix B parameter may depend on site conditions and radioactivity inventory of waste

NA = Not applicable

limiting case represented by a humid site or sites where irrigation farming has been initiated. (The humid site is also evaluated due to the uncertainty in predicting climate and site conditions over a 10,000 year period of concern.)

- Section A.4 is a summary.

A.1 PARAMETERS AFFECTING NUCLIDE MIGRATION AT A GENERIC ARID WESTERN GCDF

Several factors affect nuclide migration in unsaturated geologic media. In this section, those factors considered to have a major influence on nuclide transport will be discussed. Although reference in this discussion is made to arid site conditions, these factors also influence nuclide migration in humid regimes. This latter condition will be considered in greater detail in subsequent sections.

A.1.1 Vertical Groundwater Flow

Several investigators have shown that net vertical movement of groundwater in the vadose zone (the unsaturated region above the saturated zone) is negligible in arid regions except in the top few meters of soil. This results from a combination of two factors. First, potential evapotranspiration in arid regions greatly exceeds precipitation, usually by an order of magnitude or more. In addition, typical arid zone soils contain a caliche or argillic horizon at or near the surface which inhibits infiltration and thus deep percolation.

A study of mean annual evapotranspiration and deep percolation involving three widely separated climatic regions of the United States (Cincinnati, Ohio; Orlando, Florida; and Los Angeles, California), found that there was a net annual percolation at the subhumid sites in Cincinnati and Orlando, but at the semiarid Los Angeles site the net percolation into the soil was zero (Reference A-9). Preliminary studies (Reference A-10) being performed by the University of California at Los Angeles for the Department of Energy at the arid Nevada Test Site show that percolation into undisturbed soil at Frenchman Flat is zero below a depth of one meter.

A recent lysimeter study of soil moisture at the Hanford Reservation (Reference A-1) indicated that soil moisture content variations which are attributable to changes in solar radiation and precipitation are only apparent within the upper 1 to 2 m (3.0 to 6.5 ft). Below this depth, changes in moisture content of 1 percent or less were recorded during the year, with no significant changes in moisture content below the 12-m (39-ft) depth. Natural recharge to the unconfined aquifer from precipitation was found to be negligible.

Reference A-11, in discussing percolation in the arid southwest, states, "The formation of widespread pedogenic caliche in the arid and semiarid zones of the world also strongly suggests that precipitation only penetrates a few feet into the ground in such regions prior to evaporation and deposition of $CaCO_3$...In much of the Southwest infiltration of precipitation on interfluves rarely reaches water tables of even intermediate depth (10-100 m)."

The study also stated that ". . . precipitation falling on the valley floors underlain by carbonate rocks was not estimated because recharge to either the lower carbonate aquifer or the younger aquifers beneath such areas seems improbable under present climatic conditions."

Although net downward percolation is negligible in arid regions where a thick unsaturated zone mantles an unconfined aquifer, advection, mechanical dispersion, and diffusion of contaminants likely continues to occur at very low rates over long periods of time. Negative and positive fluxes of water and solutes can be expected. Many investigators prefer to ignore this movement when dealing with relatively short time frames. It may, however, contribute to exposure scenarios when dealing with a time frame of thousands of years.

The condition of negligible deep percolation at the generic GCDF could be temporarily altered in areas of the disposal facility where the soil has been disturbed. The absence of vegetation on the surface and disturbance of the caliche or argillic layer could contribute to net percolation through the geosphere over the burial pit or borehole. Although some downward percolation may occur immediately after facility construction, the net effect in the long term will likely continue to be negligible percolation at the depth of the GCDF when plant cover has been reestablished.

The negligible recharge by precipitation in arid regions to deep water table aquifers suggests that, for waste buried near the surface, the greatest potential for nuclide migration may be upward toward the land surface by diffusion rather than downward by advection and dispersion toward the aquifer. It thus becomes an objective of GCD to place waste at a sufficient depth to minimize the hazard from nuclides migrating both upward and downward.

A.1.2 Nuclide Retardation

The transfer of nuclides (or other contaminant mass) from pore water to the solid part of the porous medium by adsorption or other chemical processes, while flow occurs, causes the advance rate of the contaminant front to be retarded. The retardation of the front relative to the bulk mass of water is described by the relation

$$R = \frac{V}{V_c} = 1 + \frac{\rho}{\eta} K_d \qquad \text{(A-1)}$$

where

R = Retardation factor (unitless)

V = Average linear velocity (m/yr) of the groundwater (i.e., the volumetric flux divided by the actual cross-sectional area of the pores through which flow occurs)

V_c = Velocity of the center of the contaminant mass (m/yr)

ρ = Bulk mass density of the porous medium (g/ml)

η = Porosity (unitless)

K_d = Distribution coefficient (i.e., the mass of solute on the solid phase per unit mass of solid phase divided by the concentration of the solute in solution) - (ml/g)

When a mixture of reactive contaminants enters the groundwater zone, each specie will travel at a rate depending upon its particular retardation factor. After a given time, the original contaminant cloud will have segregated into different zones, each zone advancing in the same direction at different velocities. Thus, the time required for a nuclide to migrate from a waste disposal site by advection to a point of concern can be represented by the unit-compatible one-dimensional equation

$$t = \frac{xR}{V} \qquad \text{(A-2)}$$

where

t = Time (years)

x = Vertical distance from disposal facility to point of concern (meters)

R = Retardation factor (unitless)

V = Average linear velocity of the groundwater (m/yr)

A.1.3 Nuclide Decay

During the time that nuclides are migrating, they are also decaying in accordance with the relation

$$C_t = C_o(0.5)^n \qquad \text{(A-3)}$$

where

C_t = Concentration of nuclide at time t (Ci/m^3)

C_o = Initial concentration of nuclide (Ci/m^3)

$n = t/t_{\frac{1}{2}}$ or the time of concern divided by the half-life of the nuclide (unitless)

Radionuclide decay is the spontaneous transformation of a given heavy nuclide into one or more different lighter nuclides resulting in the formation of stable elements or isotopes and in a decline in the mass of the original nuclide. The primary result of this disintegration process is to make the original radioactive source more dilute with time. The objective of a waste disposal program is to isolate the radioactive materials in such a manner that sufficient time will be available for the nuclides to decay to innocuous levels before being released to the biosphere.

Isotopes generated in the intermediate decay process are called "decay daughters." Certain relatively long half-lived decay daughters (e.g. Ra-226) of Th-230, Pu-238, Pu-241, Cm-242 and Cm-244 should be taken into account when assessing the impact of waste disposal over long periods of time. The methodology for such an assessment is discussed in the latter part of this Appendix.

A.1.4 Dispersion

For homogeneous saturated media with steady-state flow, the one-dimensional form of the advection-dispersion equation describing the transport of reactive radionuclides is

$$\frac{D_x}{R}\frac{\partial^2 C}{\partial x^2} - \frac{V_x}{R}\frac{\partial C}{\partial x} - \lambda_d C = \frac{\partial C}{\partial t} \qquad \text{(A-4)}$$

where

D_x = Coefficient of hydrodynamic dispersion (m^2/yr)

R = Retardation factor (unitless)

C = Concentration of the nuclide (Ci/m^3)

x = Direction of contaminant migration

V_x = Average linear velocity of the groundwater (m/yr)

λ_d = Radioactive decay constant (yr^{-1})

t = Time

This equation indicates that the physical processes controlling the flux of a solute in the x-direction into and out of an elemental volume are hydrodynamic dispersion (the first term on the left-hand side of Equation A-4) and advection (the second term). The third term represents the loss of solute concentration in the elemental volume due to radioactive decay. The retardation factor describes the effects of solute adsorption.

Advection is the component of solute transport attributed to the bulk movement of groundwater, proceeding at a rate equal to the average linear groundwater velocity. However, in natural systems, there is a tendency for solutes to spread out from the path that they would be expected to follow based on the advective hydraulics of the flow system. This spreading phenomenon is called hydrodynamic dispersion. It occurs because of mechanical mixing during fluid advection and because of molecular diffusion due to the thermal kinetic energy of the solute particles. This is indicated by the form of the equation describing the coefficient of hydrodynamic dispersion, which can be expressed in terms of two components:

$$D_x = \alpha_x V_x + D^* \qquad \text{(A-5)}$$

where

D_x = Coefficient of hydrodynamic dispersion in the x-direction (m^2/yr)

α_x = Dispersivity (m) in the x-direction (a characteristic property of the porous medium)

V_x = Average linear groundwater velocity in the x-direction (m/yr)

D^* = Coefficient of molecular diffusion for the solute in the porous medium (m^2/yr).

Mechanical mixing or hydraulic dispersion (represented by the first term on the right-hand side of Equation A-5) occurs on a microscopic scale due to differences in the size, roughness, branching, and interfingering of pore channels, and on a macroscopic scale due to heterogeneities in the hydraulic conductivity of the system. This causes some of the water and solute molecules to travel more rapidly than the average linear velocity and some to travel more slowly. The solute thus arrives at the outflow boundary sooner but at a lower concentration than if it is affected only by advection.

The diffusion component of dispersion is the process whereby ionic or molecular species move under the influence of their kinetic activity in the direction of their concentration gradient (from high to low) regardless of the direction of bulk groundwater movement. Diffusion proceeds according to Fick's laws and ceases only when concentration gradients are in equilibrium.

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APPENDIX A

DETERMINATION OF NUCLIDE DISPOSAL CONCENTRATION LIMITS AND OPTIMAL BURIAL DEPTH

CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX A

DETERMINATION OF NUCLIDE DISPOSAL CONCENTRATION LIMITS AND OPTIMAL BURIAL DEPTH

Several different approaches have been used by various investigators to establish an upper waste concentration limit on disposal of low-level waste (LLW). Most of these limits are based on exposure to the general public through various postulated pathways. Several pathways to man that have been evaluated for shallow land burial (SLB) are essentially eliminated by deeper burial. Greater confinement disposal (GCD) places the waste below the depth where it will be directly disturbed by plant roots, burrowing animals, surface erosion and other in situ exposure scenarios. In addition, the increased soil cover associated with GCD is adequate to attenuate most of the gamma radiating waste.

Exposure pathways which must be examined for any disposal method include aquifer contamination and upgradient migration by molecular diffusion. Greater confinement disposal generally increases the risk of aquifer contamination at a given site because of the reduced distance from the disposal facility to the aquifer. In addition, because molecular diffusion follows chemical rather than hydraulic gradients, contamination may occur anywhere within the geosphere. Therefore, it is incumbent to examine both of these pathways in detail for an arid western GCDF and to determine at what optimal depth the exposure from nuclide migration in all directions can be minimized.

The purpose of this appendix is to determine the allowable waste concentration limits of nuclides and the optimal burial depth for LLW at a generic arid western GCDF site. The parameters assumed pertinent to a site characterization and migration analysis for the generic GCDF are given in Table A-1.

This appendix is divided into four sections:

- Section A.1 is a discussion of the various conditions and parameters at arid western sites which affect nuclide migration and the long-term performance of a disposal site.
- Section A.2 is a determination of the optimal depth of burial based on the plausible exposure pathways for typical low-level waste and a determination of the average allowable area disposal concentration limits for such waste and its nuclides.
- Section A.3 compares the calculated allowable area concentration limits and their waste disposal application for two extreme bounding cases: expected conditions at an arid site and the

TABLE A-1

PARAMETERS ASSOCIATED WITH NUCLIDE MIGRATION AT WASTE DISPOSAL SITES

Parameter	LASL	Hanford	NTS	INEL	Used in Calculations for Generic GCDF
Annual precipitation (cm)	40	16(a)	10(b)	22(c)	10
Thickness of vadose zone (m)	200 to 400	106(a)	213(d)	186(c)	170(e)
Soil type	weathered tuff	gravel, sand, silt(a)	alluvial tuff(f)	silt, clay(g)	sand, clay
Effective porosity of aquifer (%)	--	3 to 4(h)	2.3(d)	--	3.0
Aquifer Velocity (m/yr)	--	1000(h)	52(f)	600(c)	700
Vadose zone porosity (%)	--	--	3-48(d)	--	10%
Vadose zone bulk density (g/cm^3)	--	--	--	--	1.6
Vertical unsaturated groundwater velocity (m/yr)	--	--	--	--	0(i)
Vertical saturated groundwater velocity (m/yr) - limiting case	--	--	--	--	5(i)
Diffusion coefficient in unsaturated zone (m^2/yr)	--	--	--	--	0.1(i)
Dispersivity (m)	--	--	--	--	20(i)
Optimal Burial Depth for GCDF (m)	NA	NA	NA	NA	35(j)

TABLE A-1 (Cont)

Parameter	LASL	Hanford	NTS	INEL	Used in Calculations for Generic GCDF
Depth to bottom of GCDF (m)	NA	NA	NA	NA	40(k)
Depth of soil cover (m)	NA	NA	NA	NA	30(k)
Assumed dimensions of GCDF site (or pit concept) assumed square (m)	NA	NA	NA	NA	60(k)
Assumed borehole dimensions					
Borehole diameter (m)	NA	NA	NA	NA	2(k)
Array spacing (m)	NA	NA	NA	NA	10(l)

(a) Reference A-1
(b) Reference A-2
(c) Reference A-3
(d) Reference A-4
(e) Includes 10 meter thickness of waste
(f) Reference A-5
(g) Reference A-6
(h) Reference A-7
(i) Appendix A assumption based on Reference A-8
(j) Calculated in Appendix A.2
(k) Appendix B parameter
(l) Appendix B parameter may depend on site conditions and radioactivity inventory of waste

NA = Not applicable

limiting case represented by a humid site or sites where irrigation farming has been initiated. (The humid site is also evaluated due to the uncertainty in predicting climate and site conditions over a 10,000 year period of concern.)

- Section A.4 is a summary.

A.1 PARAMETERS AFFECTING NUCLIDE MIGRATION AT A GENERIC ARID WESTERN GCDF

Several factors affect nuclide migration in unsaturated geologic media. In this section, those factors considered to have a major influence on nuclide transport will be discussed. Although reference in this discussion is made to arid site conditions, these factors also influence nuclide migration in humid regimes. This latter condition will be considered in greater detail in subsequent sections.

A.1.1 Vertical Groundwater Flow

Several investigators have shown that net vertical movement of groundwater in the vadose zone (the unsaturated region above the saturated zone) is negligible in arid regions except in the top few meters of soil. This results from a combination of two factors. First, potential evapotranspiration in arid regions greatly exceeds precipitation, usually by an order of magnitude or more. In addition, typical arid zone soils contain a caliche or argillic horizon at or near the surface which inhibits infiltration and thus deep percolation.

A study of mean annual evapotranspiration and deep percolation involving three widely separated climatic regions of the United States (Cincinnati, Ohio; Orlando, Florida; and Los Angeles, California), found that there was a net annual percolation at the subhumid sites in Cincinnati and Orlando, but at the semiarid Los Angeles site the net percolation into the soil was zero (Reference A-9). Preliminary studies (Reference A-10) being performed by the University of California at Los Angeles for the Department of Energy at the arid Nevada Test Site show that percolation into undisturbed soil at Frenchman Flat is zero below a depth of one meter.

A recent lysimeter study of soil moisture at the Hanford Reservation (Reference A-1) indicated that soil moisture content variations which are attributable to changes in solar radiation and precipitation are only apparent within the upper 1 to 2 m (3.0 to 6.5 ft). Below this depth, changes in moisture content of 1 percent or less were recorded during the year, with no significant changes in moisture content below the 12-m (39-ft) depth. Natural recharge to the unconfined aquifer from precipitation was found to be negligible.

Reference A-11, in discussing percolation in the arid southwest, states, "The formation of widespread pedogenic caliche in the arid and semiarid zones of the world also strongly suggests that precipitation only penetrates a few feet into the ground in such regions prior to evaporation and deposition of $CaCO_3$...In much of the Southwest infiltration of precipitation on interfluves rarely reaches water tables of even intermediate depth (10-100 m)."

The study also stated that ". . . precipitation falling on the valley floors underlain by carbonate rocks was not estimated because recharge to either the lower carbonate aquifer or the younger aquifers beneath such areas seems improbable under present climatic conditions."

Although net downward percolation is negligible in arid regions where a thick unsaturated zone mantles an unconfined aquifer, advection, mechanical dispersion, and diffusion of contaminants likely continues to occur at very low rates over long periods of time. Negative and positive fluxes of water and solutes can be expected. Many investigators prefer to ignore this movement when dealing with relatively short time frames. It may, however, contribute to exposure scenarios when dealing with a time frame of thousands of years.

The condition of negligible deep percolation at the generic GCDF could be temporarily altered in areas of the disposal facility where the soil has been disturbed. The absence of vegetation on the surface and disturbance of the caliche or argillic layer could contribute to net percolation through the geosphere over the burial pit or borehole. Although some downward percolation may occur immediately after facility construction, the net effect in the long term will likely continue to be negligible percolation at the depth of the GCDF when plant cover has been reestablished.

The negligible recharge by precipitation in arid regions to deep water table aquifers suggests that, for waste buried near the surface, the greatest potential for nuclide migration may be upward toward the land surface by diffusion rather than downward by advection and dispersion toward the aquifer. It thus becomes an objective of GCD to place waste at a sufficient depth to minimize the hazard from nuclides migrating both upward and downward.

A.1.2 Nuclide Retardation

The transfer of nuclides (or other contaminant mass) from pore water to the solid part of the porous medium by adsorption or other chemical processes, while flow occurs, causes the advance rate of the contaminant front to be retarded. The retardation of the front relative to the bulk mass of water is described by the relation

$$R = \frac{V}{V_c} = 1 + \frac{\rho}{\eta} K_d \tag{A-1}$$

where

R = Retardation factor (unitless)

V = Average linear velocity (m/yr) of the groundwater (i.e., the volumetric flux divided by the actual cross-sectional area of the pores through which flow occurs)

V_c = Velocity of the center of the contaminant mass (m/yr)

ρ = Bulk mass density of the porous medium (g/ml)

η = Porosity (unitless)

K_d = Distribution coefficient (i.e., the mass of solute on the solid phase per unit mass of solid phase divided by the concentration of the solute in solution) - (ml/g)

When a mixture of reactive contaminants enters the groundwater zone, each specie will travel at a rate depending upon its particular retardation factor. After a given time, the original contaminant cloud will have segregated into different zones, each zone advancing in the same direction at different velocities. Thus, the time required for a nuclide to migrate from a waste disposal site by advection to a point of concern can be represented by the unit-compatible one-dimensional equation

$$t = \frac{xR}{V} \tag{A-2}$$

where

t = Time (years)

x = Vertical distance from disposal facility to point of concern (meters)

R = Retardation factor (unitless)

V = Average linear velocity of the groundwater (m/yr)

A.1.3 Nuclide Decay

During the time that nuclides are migrating, they are also decaying in accordance with the relation

$$C_t = C_o(0.5)^n \tag{A-3}$$

where

C_t = Concentration of nuclide at time t (Ci/m^3)

C_o = Initial concentration of nuclide (Ci/m^3)

$n = t/t_{\frac{1}{2}}$ or the time of concern divided by the half-life of the nuclide (unitless)

Radionuclide decay is the spontaneous transformation of a given heavy nuclide into one or more different lighter nuclides resulting in the formation of stable elements or isotopes and in a decline in the mass of the original nuclide. The primary result of this disintegration process is to make the original radioactive source more dilute with time. The objective of a waste disposal program is to isolate the radioactive materials in such a manner that sufficient time will be available for the nuclides to decay to innocuous levels before being released to the biosphere.

Isotopes generated in the intermediate decay process are called "decay daughters." Certain relatively long half-lived decay daughters (e.g. Ra-226) of Th-230, Pu-238, Pu-241, Cm-242 and Cm-244 should be taken into account when assessing the impact of waste disposal over long periods of time. The methodology for such an assessment is discussed in the latter part of this Appendix.

A.1.4 Dispersion

For homogeneous saturated media with steady-state flow, the one-dimensional form of the advection-dispersion equation describing the transport of reactive radionuclides is

$$\frac{D_x}{R}\frac{\partial^2 C}{\partial x^2} - \frac{V_x}{R}\frac{\partial C}{\partial x} - \lambda_d C = \frac{\partial C}{\partial t} \qquad \text{(A-4)}$$

where

D_x = Coefficient of hydrodynamic dispersion (m^2/yr)

R = Retardation factor (unitless)

C = Concentration of the nuclide (Ci/m^3)

x = Direction of contaminant migration

V_x = Average linear velocity of the groundwater (m/yr)

λ_d = Radioactive decay constant (yr^{-1})

t = Time

This equation indicates that the physical processes controlling the flux of a solute in the x-direction into and out of an elemental volume are hydrodynamic dispersion (the first term on the left-hand side of Equation A-4) and advection (the second term). The third term represents the loss of solute concentration in the elemental volume due to radioactive decay. The retardation factor describes the effects of solute adsorption.

Advection is the component of solute transport attributed to the bulk movement of groundwater, proceeding at a rate equal to the average linear groundwater velocity. However, in natural systems, there is a tendency for solutes to spread out from the path that they would be expected to follow based on the advective hydraulics of the flow system. This spreading phenomenon is called hydrodynamic dispersion. It occurs because of mechanical mixing during fluid advection and because of molecular diffusion due to the thermal kinetic energy of the solute particles. This is indicated by the form of the equation describing the coefficient of hydrodynamic dispersion, which can be expressed in terms of two components:

$$D_x = \alpha_x V_x + D^* \qquad \text{(A-5)}$$

where

D_x = Coefficient of hydrodynamic dispersion in the x-direction (m^2/yr)

α_x = Dispersivity (m) in the x-direction (a characteristic property of the porous medium)

V_x = Average linear groundwater velocity in the x-direction (m/yr)

D^* = Coefficient of molecular diffusion for the solute in the porous medium (m^2/yr).

Mechanical mixing or hydraulic dispersion (represented by the first term on the right-hand side of Equation A-5) occurs on a microscopic scale due to differences in the size, roughness, branching, and interfingering of pore channels, and on a macroscopic scale due to heterogeneities in the hydraulic conductivity of the system. This causes some of the water and solute molecules to travel more rapidly than the average linear velocity and some to travel more slowly. The solute thus arrives at the outflow boundary sooner but at a lower concentration than if it is affected only by advection.

The diffusion component of dispersion is the process whereby ionic or molecular species move under the influence of their kinetic activity in the direction of their concentration gradient (from high to low) regardless of the direction of bulk groundwater movement. Diffusion proceeds according to Fick's laws and ceases only when concentration gradients are in equilibrium.

Since the phenomenon of diffusion acts independent of direction (i.e., it contributes to migration both upward and downward), exposure pathways resulting from surface contamination as well as contamination of the aquifer must be examined. Thus, in addition to a well water ingestion scenario, consideration must be given to exposure by plant root uptake of nuclides and subsequent food consumption as well as the inhalation of nuclides which have contaminated the surface soil and been resuspended by the wind under natural or man-induced conditions.

A.2 CALCULATION OF AREA CONCENTRATION LIMITS AND OPTIMAL BURIAL DEPTH

The methodology for calculating waste disposal concentration limits and optimal burial depth for a generic GCDF assumes two primary waste management goals:

- Assure that potential exposures to man do not exceed specified limits, and
- Minimize the environmental impacts from waste burial

The first goal requires that the amount and/or type of waste inventory be limited. The second goal requires that the waste be buried at that depth which minimizes the impacts from contaminants migrating both to the surface by diffusion and to an underlying aquifer by advection and dispersion.

A.2.1 Methodology

To determine optimal burial depths and establish limits for the isotopes that could eventually migrate to the aquifer or to the surface, it is necessary to work backward from a permissible individual exposure level and set concentration limits based upon this exposure limit. The dose guideline used for the migration analysis is based on the ICRP study (Reference A-12) which recommends a dose limitation to a few non-occupationally involved individuals of 500 mrem/yr. With this limitation on exposure, one can calculate a limitation on the waste that can be disposed such that migrating nuclides will not cause this exposure guideline to be exceeded.

Calculations were performed using a computer model (Reference A-13) which first simulates the movement of the waste through the disposal site geosphere and then determines the total radioactive dosage to both individuals and populations as the result of various exposure scenarios.

Four mechanisms are used to describe the movement of waste within the geosphere:

- Downward advection of contaminants by groundwater flow (horizontal advection and dilution in the aquifer is conservatively neglected)
- Mechanical or hydraulic dispersion
- Molecular diffusion, and
- Mechanical disturbance (e.g., well drilling)

In addition, five exposure pathways have been incorporated in the model (See Figure A-1):

- Consumption of well water
- Consumption of food (crops, meat, and milk)
- Inhalation of resuspended contaminated surface soil
- Inhalation of radon gas (daughter of radium-226), and
- Direct exposure to contaminated surface soil

Equations A-4 and A-5 are used to model radioactive contaminant transport by advection, hydraulic dispersion, and diffusion at the generic site. Although the equations describe mass transport under saturated conditions, their use in this analysis of waste migration at an unsaturated generic site is warranted for two reasons. First, it can be shown that the unsaturated model is equivalent to the saturated model under the assumed condition of uniform flow (i.e., constant average linear groundwater velocity and moisture content through time and space). Because the processes of groundwater and contaminant movement in the unsaturated zone are site-specific functions of moisture content, an examination of waste migration in a generic site vadose zone using an unsaturated flow model would involve high uncertainty in parameter estimates and in the resulting model output. This does not suggest, however, that mass transport in the unsaturated zone should necessarily be modeled using Equations A-4 and A-5 at a specific site where the functional relationships describing moisture and contaminant movement can be reasonably determined.

The second reason for using a saturated-condition model for this examination concerns the long (10,000 years) assessment period. During the next 10,000 years, it is reasonable to expect that a major climatic change will occur in the West similar to the last pluvial period which ended approximately 9,000 years ago (Reference A-6). This could result in increased deep percolation and a rise in the existing water table due to recharge from precipitation, surface water bodies, and/or water diverted for irrigated agricultural activities above the waste disposal site.

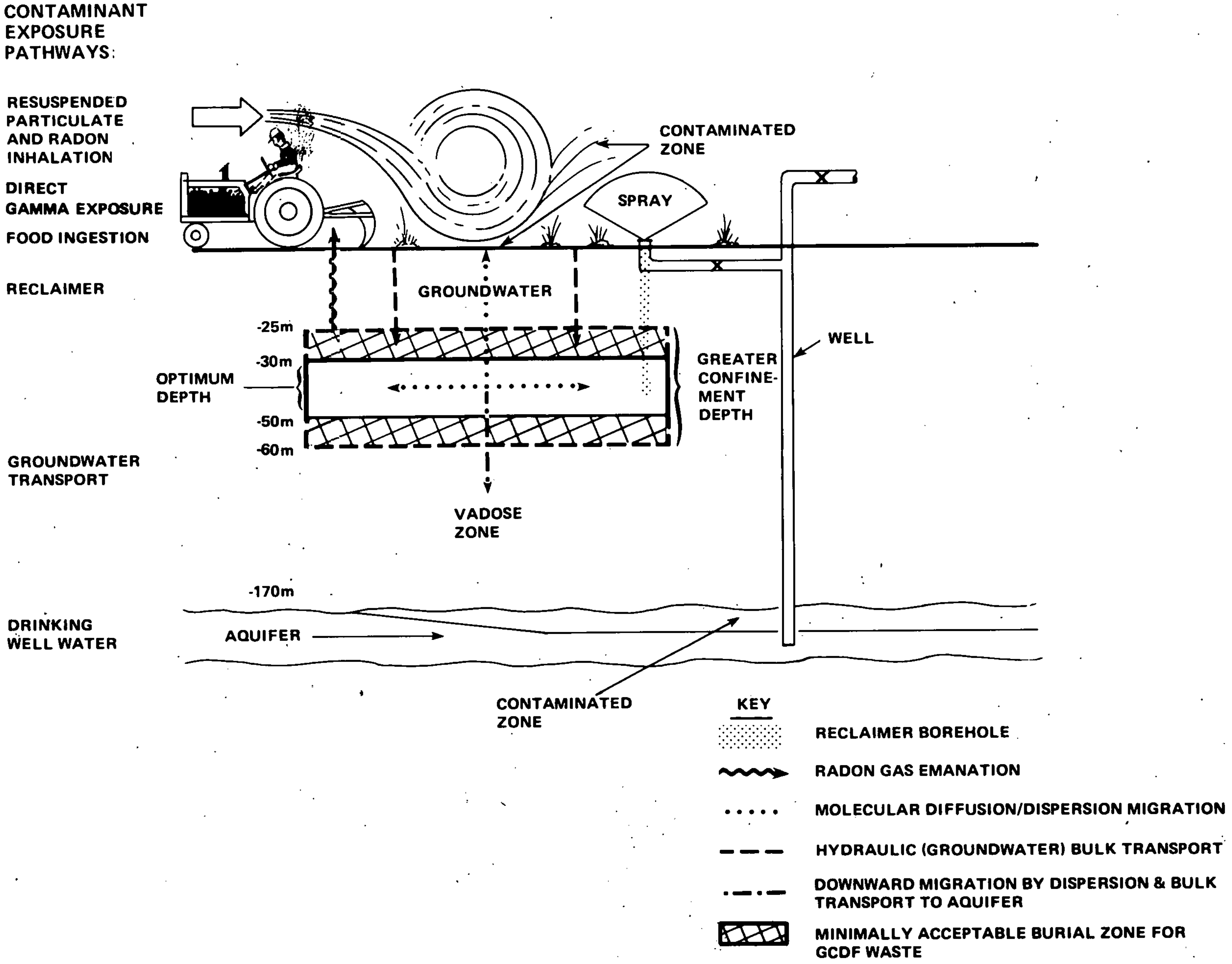

FIGURE A-1 GREATER CONFINEMENT DISPOSAL FACILITY EXPOSURE PATHWAYS

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To simplify the boundary conditions and geometry, the model conservatively assumes a homogeneous geologic medium exhibiting uniform flow and other hydrologic characteristics and a site of infinite lateral extent. The calculations are thus based on the amount of waste inventory that can be disposed of per unit surface area at the disposal site (Ci/m^2) resulting in what are called area concentration limits or ACL's. Off-site exposures are accounted for indirectly by assuming a uniform population density. Thus, as the waste is carried off site and exposes a larger population, the individual dosage is reduced.

It is also assumed that aquifer dilution does not occur, that all of the exposed individual's food and fluids are obtained from the disposal site, that the individual spends his entire life on the site and that the on-site air is not diluted by off-site air. Further, the inventory limits which are calculated are based on peak exposure rates.

To bound the analysis, differences in site conditions between the current (arid) and potential (humid) state were modeled by varying the downward velocity of groundwater movement between zero and 5 m/yr respectively. (Intermediate velocities of 0.5 and 0.05 m/yr were also used.) All other parameters were assumed to remain unchanged. The potential humid site conditions were found to represent the limiting case for determining disposal waste concentration limits.

Movement of the waste by mechanical disturbance is modeled by assumimg that the probability of the waste being disturbed is proportional to the period of concern (i.e., 10,000 years). The disturbance could occur as a result of a number of reclaimer activities including drilling, basement construction, excavation, tilling, etc. It was assumed that within the 10,000 year period surface disturbances are limited to 10 percent of the top one meter of the geosphere. At greater depths, the probability of disturbance is assumed to be inversely proportional to the depth of the contaminant. Thus the annual probability of mechanically bringing contaminated waste to the surface is 0.1/10,000 per year (or 10^{-5}/yr) divided by the depth of the contamination. For the well drilling scenario, it is assumed that the waste is mixed with the soil which has been drilled and that a new well for every four persons served would need to be drilled every 100 years. An erosion rate of 0.001 m/yr has also been assumed to simulate the reductions in cover over the facility.

A typical LLW mix of isotopes was used for the analysis (see Table A-2). All calculations of ACL's and optimal depth were made based on this mix as a whole and/or the individual isotopes comprising the mix. The isotopes contained in this LLW mix all have half-lives greater than 10 years. It was assumed that isotopes with shorter half-lives would decay too rapidly to be of concern during the postoperational period of a waste disposal facility. The significant decay daughters of Th-230, Pu-238, Pu-241, Am-241, Cm-242, and Cm-244 are also included

TABLE A-2

NUCLIDE SPECIFIC PARAMETERS FOR REFERENCE LOW-LEVEL WASTE

Isotope	Half-Life (yr)	Specific Activity (Ci/m^3)	Retardation(a) Factor	LLW Concentration(b) (Ci/m^3)
H-3	1.2E+1(c)	2.9E+9	1.0E+0	1.0E-1
C-14	5.7E+3	1.0E+5	1.0E+1	4.0E-3
Ni-59	8.0E+4	6.8E+5	3.3E+2	1.0E-2
Ni-63	1.0E+2	5.3E+7	3.3E+2	2.0E-0
Sr-90	2.9E+1	3.6E+8	1.0E+2	5.0E-3
Tc-99	2.1E+5	1.0E+4	1.0E+0	3.0E-5
I-129	1.6E+7	8.5E+2	1.0E+0	6.0E-6
Cs-135	2.3E+6	2.4E+3	1.0E+3	3.0E-5
Cs-137	3.0E+1	1.7E+8	1.0E+3	9.0E-1
Ra-226	1.6E+3	4.9E+6	5.0E+2	1.0E-4
Th-230	7.7E+4	3.8E+5	1.0E+4	7.1E-5
U-234	2.4E+5	1.2E+5	1.4E+4	2.0E-3
U-235	7.0E+8	4.1E+1	1.4E+4	3.0E-5
U-238	4.5E+9	6.4E+0	1.4E+4	7.0E-4
Np-237	2.1E+6	1.3E+4	1.0E+2	5.0E-8
Pu-238	8.8E+1	3.4E+8	1.0E+4	3.0E-4
Pu-239	2.4E+4	1.2E+6	1.0E+4	4.0E-5
Pu-240	6.5E+3	4.7E+6	1.0E+4	7.0E-5
Pu-241	1.5E+1	2.2E+9	1.0E+4	2.0E-2
Pu-242	3.9E+5	7.6E+4	1.0E+4	2.0E-7
Am-241	4.3E+2	6.4E+7	1.0E+4	3.0E-5
Am-243	7.4E+3	3.5E+6	1.0E+4	2.0E-6
Cm-242	4.5E-1	4.0E+7	3.3E+3	2.5E-3
Cm-244	1.8E+1	1.6E+9	3.3E+3	2.0E-4
LLW	---	2.8E+4	---	3.0E+0

(a) Reference A-14

(b) Reference A-15

(c) 1.2E+1 ≡ 1.2 x 10^1 ≡ 12

since they are generated following disposal of the parent nuclides. The LLW reference mixture is similar to a mixture of typical commercial low-level wastes with the activation products Ni-59 and Ni-63 added to simulate waste from decommissioning of reactors and fuel-cycle facilities (either commercial or DOE).

Other assumptions used in the calculations are listed as follows:

- Waste which migrates to the surface was assumed to be taken up by surface vegetation using the bioaccumulation rates (Reference A-16) given in Table A-3. The vegetation in turn, was assumed to be consumed as crops by man at the rate of 195 kg/yr along with 95 kg/yr of meat, and 110 l/yr of milk (Reference A-16).

- Waste which migrates to the underlying aquifer was assumed to be ingested as contaminated well water at a rate of 370 liters/yr (Reference A-16).

- The fraction of waste dissolved in the groundwater was assumed to be equal to the reciprocal of the retardation factor.

- The airborne particulate inhalation pathway assumes the resuspension of waste particulates mixed in with soil which is farmed or blown by desert winds. The resuspension rate is 100 micrograms/cubic meter (Reference A-17).

- The airborne dust is inhaled along with radon gas emanating from the site at the ambient concentration. The inhalation rate is 7,300 cubic meters/year (Reference A-16).

- The waste container life was assumed to be 100 years.

- Analysis was terminated at 10,000 years because of the need for a realistic calculational time frame. Any isotope located within ten to a few hundred meters of the biosphere, which requires more than 10,000 years to reach its maximum concentration, was considered immobile.

- In the case of certain long-lived nuclides, e.g., uranium-238, the average ACL would be nearly equivalent to the specific activity of the nuclide since the maximum concentration would not reach the biosphere until a time well beyond 10,000 years. The actual health hazard from such material is no greater than unmined uranium ore in equilibrium with the soil.

TABLE A-3

EXPOSURE PATHWAY ANALYSIS PARAMETERS

Isotope	Concentration Plant/Soil Ratio(a)	Ingestion Df (mrem/yr per pCi)(a)	Inhalation Df (mrem/yr per pCi)(a)	Ingestion Organ Weighting Factor(b)	Inhalation Organ Weighting Factor(b)
H-3	4.8E+0(b)	1.3E-7	1.3E-7	1.0E+0	1.0E+0
C-14	5.5E+0	2.8E-6	2.3E-6	3.0E-2	1.2E-1
Ni-59	1.9E-2(c)	1.6E-6	8.2E-6	1.0E+0	1.2E-1
Ni-63	1.9E-2	1.3E-4	5.4E-5	3.0E-2	1.2E-1
Sr-90	1.7E-2	1.9E-3	1.2E-2	1.0E+0	1.2E-1
Tc-99	2.5E-1	6.1E-7	1.4E-4	3.0E-1	1.0E+0
I-129	2.0E-2	7.2E-3	6.9E-6	3.0E-2	1.0E+0
Cs-135	1.0E-2	8.0E-6	1.3E-5	1.0E+0	3.0E-1
Cs-137	1.0E-2	7.1E-5	7.8E-5	1.0E+0	1.0E+0
Ra-226	3.1E-4	2.2E-1	3.0E+1	1.0E+0	1.0E+0
Th-230	4.2E-3	2.1E-3	2.3E+0	3.0E-1	3.0E-1
U-234	2.5E-3	8.4E-4	5.0E-2	1.2E-1	1.2E-1
U-235	2.5E-3	8.0E-4	4.9E-2	1.2E-1	1.2E-1
U-238	2.5E-3	7.7E-4	4.6E-2	1.2E-1	1.2E-1
Np-237	2.5E-3	1.4E-3	1.7E+0	1.2E-1	1.2E-1
Pu-238	2.5E-4	6.7E-4	2.7E+0	1.2E-1	1.2E-1
Pu-239	2.5E-4	7.6E-4	3.1E+0	1.2E-1	1.2E-1
Pu-240	2.5E-4	7.6E-4	3.0E+0	1.2E-1	1.2E-1
Pu-241	2.5E-4	1.6E-5	6.0E-2	1.2E-1	1.2E-1
Pu-242	2.5E-4	7.2E-4	2.9E+0	1.2E-1	1.2E-1
Am-241	2.5E-4	4.0E-4	4.9E-1	3.0E-1	3.0E-1
Am-243	2.5E-4	4.0E-4	4.9E-1	3.0E-1	3.0E-1
Cm-242	2.5E-3	7.9E-5	1.2E-2	3.0E-1	3.0E-1
Cm-244	2.5E-3	4.9E-4	2.5E-1	3.0E-1	3.0E-1

(a) Reference A-16
(b) Reference A-12
(c) 4.8E+0 = 4.8 x 10^0 ≐ 4.8
(d) 1.9E-2 = 1.9 x 10^{-2} ≐ 0.019

Using the contaminant transport and mechanical disturbance models, the concentrations of wastes at the surface and in the underlying aquifer are calculated for the two extreme cases. These concentrations then serve as inputs to the various exposure scenarios for determining dose rates.

The process of determining an optimal depth of burial for low-level wastes can be divided into two steps:

- Ascertain the depth required to assure, with reasonable probability, that the waste will not be unintentionally disturbed by man, plant, or animal and
- Determine the effect of varying the burial depths on the potential environmental impacts resulting from waste migration.

It is generally conceded that a cover depth of approximately 10 m is sufficient to prevent intrusion by plants or burrowing animals. Beyond this, to determine the impacts to man, the potential exposure to radioactive contaminants through consumption of well water obtained from an aquifer beneath the waste was balanced against the potential exposure from mechanical disturbances, resuspended dust, radon gas, direct gamma exposure, and food consumption (vegetation, meat and milk) above the waste.

The optimal burial depth for the GCDF was determined by varying the mean depth of the facility between zero and 60 meters and determining the impacts resulting from burial at each depth. At each depth, the dose rates from the various surface phenomena and well water exposure scenarios were summed to derive the total exposure resulting from the mix. The initial concentration of the mix which would result in an exposure of 500 mrem/yr was then determined. The optimal depth was considered to be that depth at which the largest LLW inventory could be placed without exceeding the 500 mrem/yr standard.

A.2.2 Example of Exposure Pathway Dose Assessment

The well water scenario is presented as an example of the use of an exposure pathway analysis to calculate the allowable concentration levels in a source stream. These concentrations are then used in conjunction with the nuclide migration equations A-4 and A-5 to derive the allowable disposal ACL's. In the well water scenario, the assumption is made that at some future date after institutional control of the disposal facility has been relinquished, a well will be drilled into an aquifer containing groundwater that has leached through the buried waste. Water from this well is then assumed to be used for ordinary household purposes, including human consumption.

The equation which relates ingestion exposure to an allowable concentration of nuclides in the water is:

$$C_W = \frac{500\ \text{mrem/yr}}{370\ \text{l/yr} \times \text{DF mrem/pCi} \times W} = \frac{1.35\ \text{pCi/l}}{\text{DF} \times W} \qquad \text{(A-6)}$$

where

C_W = Allowable concentration of the nuclide in the well water (pCi/l)

500 mrem/yr = Individual dose guideline (Reference A-12

370 l/yr = Average yearly adult water consumption (Reference A-16

DF = Adult dose factor (mrem/pCi), a measure of the effective radiation given off by each picocurie of ingested contaminated material (Reference A-16)

W = Organ weighting factor (unitless), a measure of the relative susceptibility of a given organ to damage from ingestion of an isotope (Reference A-16)

Dose factors (Reference A-16) and organ weighting factors (Reference A-12) for the various isotopes in the reference low-level waste mix are presented in Table A-3. Critical organs were determined based on the maximum product of the dose factor and the weighting factor for each organ. These factors and the consumption rate have been combined into one term in Table A-4 representing a nuclide specific dose conversion parameter for each major exposure pathway.

The calculated allowable well water concentration limits (in pCi/l) for several nuclides of concern are shown in Table A-5. This is the concentration that, if present in water that is ingested at the rate of one liter per day (370 l/yr), would give an annual dose of 500 mrem/yr. These concentration limits should not be compared with the disposal concentration limits or ACL's. The waste (or nuclide) concentration in the well water, C_W, represents the portion of the original concentration of the waste (or nuclide), which eventually enters an aquifer and is ingested. Doses from other exposure scenarios are summed with C_W prior to determining the ACL. A similar calculational procedure can be used to ascertain the maximum allowable concentration limits for exposure from food consumed after plant uptake of nuclides and for exposure due to inhalation of resuspended contaminated dust.

A.2.3 Determination of Optimal Burial Depth

Results of computations to determine the optimal burial depth for the typical LLW mix are shown in Figure A-2. The two curves indicate the range of values arrived at by varying the

TABLE A-4

EXPOSURE PATHWAY ANALYSIS DOSE CONVERSION PARAMETERS (rem/yr/Ci/m^3)

Isotope	Water(a)	Food	Inhalation	Direct Exposure
H-3	5.0E+1(b)	1.0E+2	1.6E-5	0.0E+0
C-14	3.2E+1	1.0E+2	3.3E-5	0.0E+0
Ni-59	6.0E+2	3.4E+1	1.2E-4	0.0E+0
Ni-63	1.4E+3	8.2E+1	7.9E-4	0.0E+0
Sr-90	6.9E+5	3.2E+3	1.8E-1	0.0E+0
Tc-99	6.7E+1	5.8E+1	2.0E-2	0.0E+0
I-129	8.0E+4	5.2E+1	8.4E-4	1.8E+2
Cs-135	3.0E+3	1.1E+1	4.7E-4	0.0E+0
Cs-137	2.6E+4	1.0E+2	9.5E-3	1.1E+3
Ra-226	8.2E+7	1.4E+4	3.6E+3	1.6E+3
Th-230	2.3E+5	5.0E+2	8.4E+1	1.6E+3
U-234	3.7E+4	2.4E+1	7.6E-1	1.6E-1
U-235	3.6E+4	2.3E+1	7.2E-1	8.0E+2
U-238	3.4E+4	2.2E+1	6.7E-1	2.8E+1
Np-237	6.1E+4	4.0E+1	2.5E+1	3.5E+2
Pu-238	3.0E+4	1.9E+0	3.9E+1	3.3E-1
Pu-239	3.4E+4	2.2E+0	4.5E+1	2.0E-1
Pu-240	3.4E+4	2.2E+0	4.5E+1	3.3E-1
Pu-241	6.9E+2	4.0E-2	8.9E-1	1.2E+0
Pu-242	3.2E+4	2.9E+0	4.2E+1	2.8E-1
Am-241	4.4E+4	2.9E+0	1.8E+1	4.5E+1
Am-243	4.4E+4	2.8E+0	1.8E+1	3.3E+2
Cm-242	8.8E+3	5.7E+0	4.3E-1	1.4E+0
Cm-244	5.4E+5	3.5E+2	9.3E+0	7.3E-1

(a) Water dose conversion parameter to be divided by the retardation

(b) 5.0E+1 = 5.0 x 10^1 = 50

TABLE A-5

NUCLIDE CONCENTRATION LIMITS IN WELL WATER

Nuclide	Dose Factor[a] (DF) (mrem/pCi)	Calculated Concentration Limit in Well Water (C_w) (pCi/l)
C-14	2.84E-6[b]	4.8E+5
Tc-99	6.08E-7	2.2E+6
I-129	9.22E-6	1.5E+5
Th-232	1.50E-4	9.0E+3
Np-237	1.38E-3	9.8E+2
U-235	4.86E-5	2.8E+4
U-238	4.54E-5	3.0E+4

(a) Reference A-18

(b) $2.84E-6 \equiv 2.84 \times 10^{-6}$

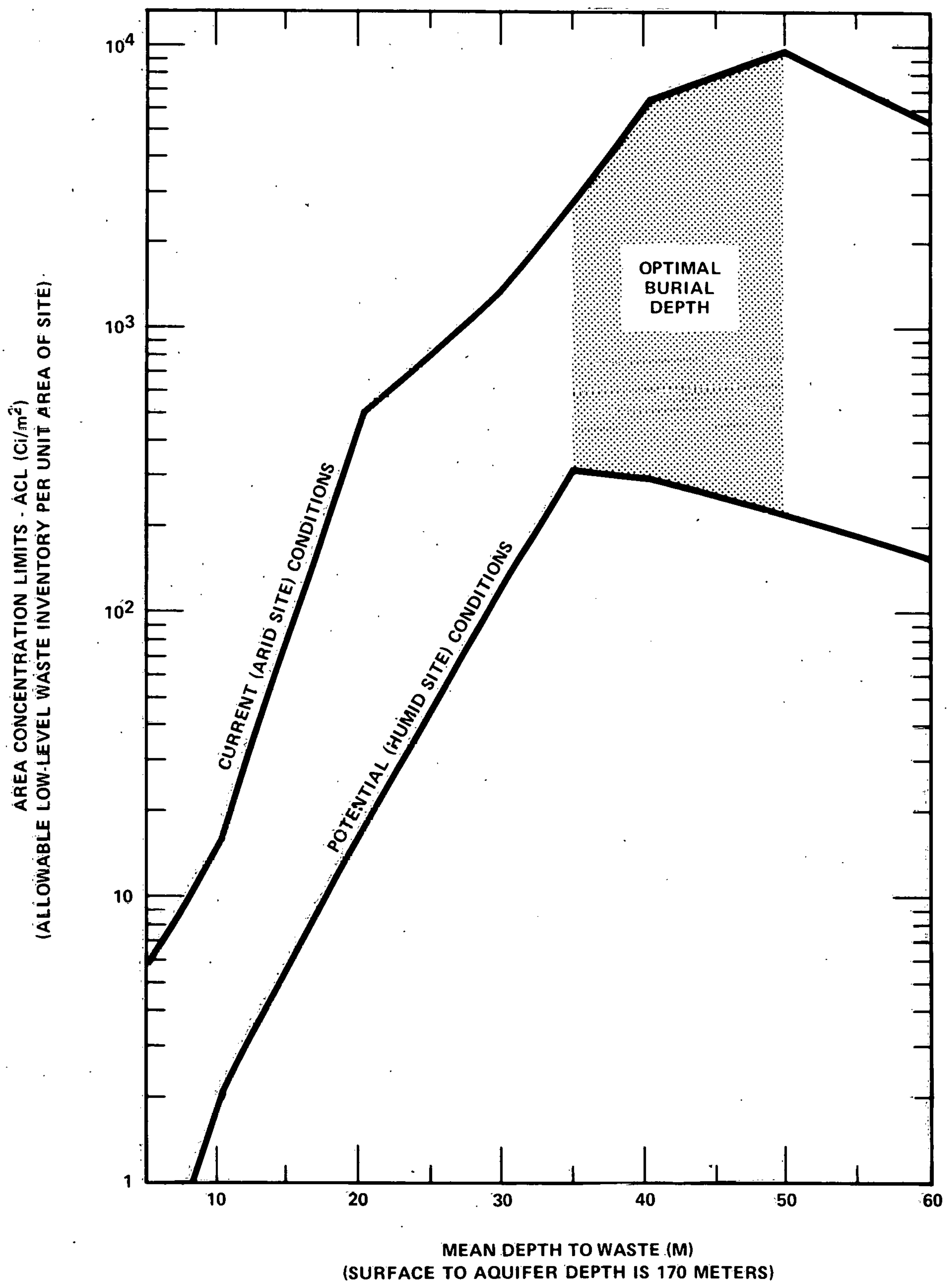

FIGURE A-2 ALLOWABLE AREA CONCENTRATION LIMITS FOR DISPOSED LOW-LEVEL WASTE AS FUNCTION OF BURIAL DEPTH

FBDU 343-001

downward groundwater velocity to account for current (arid) and potential (humid) conditions. The lower curve is the most conservative case (i.e., allows the smallest waste inventory) and thus provides the basis for the allowable area concentration limits (ACL's) and an analysis of radiological hazards. Based on this curve, an optimal mean burial depth of 35 meters was chosen. At this depth, a LLW mix inventory of 330 Ci/m^2 or less could be disposed of without exceeding the individual non-occupational exposure limit of 500 mrem/yr.

A.2.4 Determination of Allowable Area Concentration Limits

Based on the parameter values and assumptions previously presented, allowable area concentration limits for a mean burial depth of 35 meters were calculated for the typical LLW mix and the individual isotopes comprising the mix. Table A-6 lists the calculated ACL'S for the two extreme hydrologic conditions, (viz. the current arid site versus the limiting case humid site conditions). Note that Table A-6 is equivalent to Table 6-1 of Section 6.2.6 of this document except that Table A-6 does not include disposal concentration limits for shallow land burial. The "No Limit" designation indicates that the calculated limit is greater than the specific activity of the isotope. In other words, the pure isotope could safely be disposed of without the exposure standard (500 mrem/yr) being exceeded.

It is significant to note that a difference of more than nine orders of magnitude exists between the smallest and largest ACL's. Further, many of the isotopes with the smallest ACL's are usually not inventoried prior to the disposal of wastes. Since these isotopes represent the greatest radiologic hazard in terms of volume, greater care is required in inventorying radioactive waste.

A.3 APPLICABILITY AND COMPARISON OF CALCULATED AREA DISPOSAL CONCENTRATION LIMITS FOR ARID AND HUMID SITE CONDITIONS

Two scenarios or cases were evaluated in the determination of average allowable area concentration limits for buried waste at the GCDF. An expected case is representative of the currently existing conditions at most arid western sites, and a limiting case is more nearly representative of the conditons at a humid site with a deep aquifer or at an arid site where irrigation farming has been initiated.

The ACL's for the arid and humid site conditions shown in Figure A-2 differ by a factor of 10 at the optimal burial depth of 35 meters, and a factor of 50 at the greater burial depth of 50 meters, in calculating the potential exposures from the competing pathways of nuclide migration release. The results of the arid site analysis indicate that, for a vertical unsaturated zone water velocity of zero and other assumed arid site parameters, high specific activity wastes may be safely disposed of in significant quantities, given a sufficiently thick cover.

TABLE A-6

AREA CONCENTRATION DISPOSAL LIMITS FOR MOBILE NUCLIDES(a,b,c)

Nuclide	Humid Site(d) Greater Confinement (Limiting Case)	Arid Site(e) Greater Confinement (Expected Case)
	Area Concentration Limits ACL(Ci/m^2)	Area Concentration Limits ACL(Ci/m^2)
H-3	9.4E+2(f)	6.5E+6
C-14	2.3E+0	3.8E+0
Ni-59	3.7E+0	2.4E+2
Ni-63	2.2E+2	2.4E+4
Sr-90	3.6E+1	5.1E+3
Tc-99	1.1E+0	1.1E+0
I-129	1.1E-3	5.0E-2
Cs-135	1.6E+1	6.9E+2
Cs-137	1.2E+4	1.3E+4
Ra-226	1.1E-2	6.3E+0
Th-230	9.9E-3	3.8E-1
U-234	1.4E+1	3.1E+2
U-235	4.0E-1	9.3E+0
U-238	(g)	(g)
Np-237	1.3E-1	1.9E+1
Pu-238	2.3E+4	5.4E+4
Pu-239	5.5E+0	2.1E+2
Pu-240	1.1E+1	4.2E+2
Pu-241	6.8E+4	2.1E+6
Pu-242	4.5E+0	1.7E+2
Am-241	2.4E+3	7.6E+3
Am-243	1.4E+0	5.1E+1
Cm-242	2.1E+6	(g)
Cm-244	2.4E+3	1.5E+5
Unidentified LLW	3.3E+2	2.9E+3

(a) Based on Pathway Analysis developed in this Appendix

(b) Application of ACL's discussed in Appendix B

(c) Assumed site parameters for both humid and arid site: 170 m depth to aquifer, 30 m cover, 10 m waste thickness, 100 yr container life, .001 m/yr erosion rate and an intrusion rate of 3×10^{-7}/yr at the 35 meter depth

(d) Assumes for humid conditions: a vertical groundwater velocity of 5m/yr and dispersion of 100 m^2/yr

(e) Assumes for arid conditions: a zero vertical groundwater velocity and dispersion of 0.1 m^2/yr

(f) 9.4E+2 = 9.4×10^2 = 940

(g) The calculated allowable area concentration limit, ACL, exceeds the specific radioactivity of the nuclide

These results, although based on conservative assumptions, are believed to realistically represent what might be expected to occur at most western waste disposal sites (e.g. NTS, Hanford, INEL). However, if certain parameters used (e.g., the retardation factors or the dispersion coefficients) were significantly in error, the resulting potential exposures could be greately understated. Therefore, the more conservative humid site analysis was performed to represent a limiting case, thus providing a lower bound to the ACL's based on the possibility that either the selected values chosen for the parameters or the assumptions about conditions at the arid site are greatly in error.

For the humid site analysis, an average vertical groundwater velocity of 5 m/yr was used. This velocity is high compared to assumed existing generic site conditions, and may not be achieved even if there were large climatic and/or land use (i.e., irrigation) changes at the generic western site. This high velocity was chosen to accommodate uncertainties in all of the parameters rather than just the uncertainty in the current and future vertical groundwater velocities. The velocity of 5 m/yr corresponds generally to conditions at a site with rainfall of 1 m/yr (such as at a humid eastern site), 50 percent evaporation, and an effective porosity of 10 percent. This velocity is also roughly equivalent to the "Darcy" velocity for saturated soils of moderate permeability.

The humid site ACL's are still very large compared to concentrations found in most high-specific activity, low-level radioactive wastes. Thus, while the results of the arid site case (V = 0) can be used as the expected performance of a generic arid site, the humid site results (V = 5 m/yr.) can be used as a limiting case to establish restrictions which assure satisfactory performance of an arid GCD site under wide variations in parameters or conditions.

A detailed discussion on the application of the ACL's follows in Appendix D. The underlying principle of applying the ACL's is given by Equation A-7.

$$\sum_{i=1}^{24} Q_i/ACL_i < A \qquad \text{(A-7)}$$

where

Q_i = Total inventory of the ith isotope (Ci)

ACL_i = ACL of the ith isotope (Ci/m^2)

A = Total site surface area dedicated to disposal (m^2)

i = Summation index for the 24 isotopes listed in Table A-6 of this appendix and in Table 6-1.

In other words, the conditions assumed by the methodology discussed in this appendix will be satisfied if the sum of the total quantity of each isotope divided by the respective ACL is less than the surface area of the site dedicated to the disposal of those wastes. The dedicated surface area for given wastes can include any other area not already dedicated to other wastes and may include dedicated areas not part of but in the near vicinity of the disposal site.

A.4 SUMMARY

In summary, the results given indicate that, for a western arid site, the optimal mean depth of burial would be in the range of 35 to 50 meters. This assumes a disposal facility with a waste thickness of 10 to 20 meters. It may be necessary to divide the recommended average ACL's by the waste thickness in meters if the buried waste is stacked in a large pit (i.e., to thus determine the average allowable waste concentration in the pit in Ci/m^3). However, for most waste burial concepts (including borehole arrays, trenches, and smaller pits) the assumption of a source term in an infinite slab with no intervening space (i.e., a solid matrix) is very conservative and generally overstates the physical size of the source term. Therefore, the ACL's can be reasonably used as limits of inventory buried per unit site area (Ci/m^2) as given in Table A-6 even if the waste layer (e.g., in a borehole) is a few tens of meters thick. Individual waste containers, with nuclide specific inventories exceeding the ACL's may also be acceptable providing the total area requirements for mixed waste disposal at the site do not exceed the total available dedicated area for waste disposal at the site. For short-lived isotopes (e.g., H-3, Sr-90, CS-137), the ACL's can be increased to allow for additional decay time if containers are designed with an expected lifetime greater than the assumed 100 years. For containers of waste which are not designed to last 100 years, the ACL's would correspondingly be reduced for the shorter half-lived isotopes.

It must be emphasized that the nuclide disposal concentration limits calculated in this appendix should be considered as guidelines and as used here apply only to the generic (arid western) GCDF defined in this document. The limits are based on conservative assumptions due to the uncertainties involved regarding specific site conditions. Disposal limits which exceed those listed here for any particular sites may be determined using the specific parameters that are applicable to that site.

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APPENDIX B

APPLICATION OF AREA DISPOSAL CONCENTRATION LIMITS TO WASTE DISPOSAL AT A GENERIC GREATER CONFINEMENT DISPOSAL SITE

CONTENTS

LIST OF TABLES

APPENDIX B

APPLICATION OF AREA DISPOSAL CONCENTRATION LIMITS TO WASTE DISPOSAL AT A GENERIC GREATER CONFINEMENT DISPOSAL SITE

This appendix provides a set of example calculations to demonstrate the application of the area waste disposal concentration limits (ACL's) given in Table B-1 for waste disposal operations at a site selected for a generic greater confinement disposal facility (GCDF). Greater confinement disposal (GCD) is burial of waste at greater depths (30-50 m) than is the current practice for shallow land burial.

The following paragraphs describe how the concentration guidelines are to be applied to assure safe waste management operations at a generic western site.

B.1 COMPLIANCE WITH AREA WASTE DISPOSAL CONCENTRATION LIMITS

An essential function of compliance with the GCD criteria is to assure the area disposal concentration limit (ACL) guidelines given in Table B-1 are satisfied. The guidelines are assumed to represent the concentration of a radionuclide species that would be permitted if the waste was homogenously mixed and distributed in an infinitely dimensioned slab about 1 m thick. The concentration limits are determined on the basis of an analysis of several pathways of exposure discussed in Appendix A, and assumes a maximum individual dose of 500 mrem/yr. The concentration limits are calculated for expected arid site conditions and limiting case humid site conditions and listed in Table B-1.

For expected arid site conditions, the climate remains arid and hydrology is characterized by a net moisture velocity of zero where nuclide migration is controlled by diffusion with an assumed diffusion coeffient of 0.1 m^2/yr. Under these conditions, somewhat greater quantities of waste can be disposed at a western greater confinement disposal facility with a sufficiently deep (170 m) aquifer as indicated by the higher ACL's in Column B of Table B-1.

The humid site-limiting case conditions assumes the hydrology is characterized by a moisture velocity of 5 m/yr (effectively 1,000 times larger than an equivalent effective moisture velocity of 0.005 m/yr based on a diffusion coefficient of 0.1 m^2/yr). This velocity should be consistent with the conditions that could exist if irrigation farming is conducted at the site or if a major climate change occurs resulting in much higher levels of precipitation. For these conditions, the concentration limits are given in Column A of Table B-1. Because there is no way to predict the site ownership, utilization, or climatic conditions that may exist at the site after one or two hundred years and into the distant future, use of the concentration limits for the limiting case is recommended as a

TABLE B-1

AREA CONCENTRATION DISPOSAL LIMITS FOR MOBILE NUCLIDES(a,b,c)

Nuclide	Humid Site(d) Greater Confinement (Limiting Case) Area Concentration Limits ACL(Ci/m^2)	Arid Site(e) Greater Confinement (Expected Case) Area Concentration Limits ACL(Ci/m^2)
H-3	9.4E+2(f)	6.5E+6
C-14	2.3E+0	3.8E+0
Ni-59	3.7E+0	2.4E+2
Ni-63	2.2E+2	2.4E+4
Sr-90	3.6E+1	5.1E+3
Tc-99	1.1E+0	1.1E+0
I-129	1.1E-3	5.0E-2
Cs-135	1.6E+1	6.9E+2
Cs-137	1.2E+4	1.3E+4
Ra-226	1.1E-2	6.3E+0
Th-230	9.9E-3	3.8E-1
U-234	1.4E+1	3.1E+2
U-235	4.0E-1	9.3E+0
U-238	(g)	(g)
Np-237	1.3E-1	1.9E+1
Pu-238	2.3E+4	5.4E+4
Pu-239	5.5E+0	2.1E+2
Pu-240	1.1E+1	4.2E+2
Pu-241	6.8E+4	2.1E+6
Pu-242	4.5E+0	1.7E+2
Am-241	2.4E+3	7.6E+3
Am-243	1.4E+0	5.1E+1
Cm-242	2.1E+6	(g)
Cm-244	2.4E+3	1.5E+5
Unidentified LLW	3.3E+2	2.9E+3

(a) Based on Pathway Analysis developed in Appendix A.

(b) Application of ACL's discussed in this Appendix.

(c) Assumed site parameters for both humid and arid site: 170 m depth to aquifer, 30 m cover, 10 m waste thickness, 100 yr container life, .001 m/yr erosion rate and an intrusion rate of 3x10^{-7}/yr at the 35 meter depth.

(d) Assumes for humid conditions: a vertical groundwater velocity of 5m/yr and dispersion of 100 m^2/yr.

(e) Assumes for arid conditions: a zero vertical groundwater velocity and dispersion of 0.1 m^2/yr.

(f) 9.4E+2 = 9.4x10^2 = 940.

(g) The calculated allowable area concentration limit, ACL, exceeds the specific radioactivity of the nuclide.

conservative approach for waste management activities at most sites.

B.2 VERIFICATION OF ACCEPTABLE WASTE CONCENTRATION FOR A GCD WASTE DISPOSAL SITE

The primary goal of safe waste management operations is to assure that the near- and long-term aspects of waste disposal at a site will not impose an unacceptable public hazard. To accomplish this goal, a waste disposal site operator must follow safe waste management and handling practices and assure that the criteria for average waste concentrations disposed at the site are satisfied.

Satisfaction of the criteria for acceptability of waste buried at a waste disposal site can be determined by summing the inventory contributions of various nuclides in the waste as a fraction of the average area concentration limits and dividing by the total site area dedicated to waste disposal at the site. The criteria are satisfied if the site loading fraction, F_s is less than unity as provided by the formulation in Equation B-1.

$$F_s = F_o + \frac{1}{A_s} \sum_{i}^{n} \frac{Q_i}{ACL_i} \qquad \text{(B-1)}$$

where $F_s \leq 1$

and

i = The summation index designating the nuclides comprising the waste (shown in Table B-1)

F_s = The waste loading fraction for the site

F_o = The existing loading fraction for the site from previously loaded waste

Q_i = The nuclide inventory in the subject waste material (Curies) or the total inventory of each source of waste material as represented by the dominant nuclide

ACL_i = The average nuclide specific area disposal concentration limit from Table B-1 (Curies/m^2)

A_s = The surface area of the site that has been dedicated for the disposal of waste (m^2)

n = The number of nuclides listed in Table B-1 (i.e. 24)

The following example illustrates the application of Equation B-1:

A waste disposal site operator has a new site with 36 drilled waste disposal cells, each 2 m in diameter, with a cell-to-cell spacing of 10 m on center (i.e., the excluded area or buffer zone surrounding each individual cell being 100 m^2). The total dedicated area for GCD at the site is thus 3600 m^2 (approximately 0.9 acres). It is assumed a waste generator wants to ship to the disposal site 100 capsules of high specific activity strontium flouride ($^{90}SrF_2$) with a total inventory of 100,000 curies. The ACL for Sr-90 is 36 Ci/m^2. The generator also wants to ship 100 capsules of cesium fluoride ($^{137}CsF_2$), likewise with a total of 100,000 curies. The ACL for Cs-137 however is 12,000 Ci/m^2. The waste is to be disposed in a 2 m diameter by 10 m deep waste cell with 30 m of cover depth.

The site loading fraction, F_s, for the 100 Sr-90 capsules is calculated as follows: (In our example the new site implies F_o is zero.)

$$F_s(\text{Sr-90}) = \frac{1}{3600} \times \frac{100{,}000}{36} = .77$$

The 100 capsules of Sr-90 with an inventory as represented above can be safely disposed at the site even if the individual capsule inventory exceeds the ACL for strontium-90.

The site loading fraction for the capsules of Cs-137 waste is calculated as follows:

$$F_s\ (\text{Cs-137}) = \frac{1}{3600} \times \frac{100{,}000}{12{,}000} = .0023$$

The total site loading fraction is the sum of the loading fractions for each waste type being added plus the existing loading fraction for the site. (In our example the new site implies F_o is zero.)

For our example where the waste types are represented by 100 SrF_2 and 100 CsF_2 capsules:

$$F_s\ (\text{site}) = F_o\ (\text{existing waste}) + F_s\ (\text{Sr-90}) + F_s\ (\text{Cs-137})$$

$$F_s\ (\text{site}) = 0 + .77 + .0023 = .77 \text{ which is } <1$$

For a mixture of cesium and strontium sources as indicated above, it may be possible to increase the strontium inventory by 30 percent and still meet the waste disposal criteria for the site. On the other hand we could increase the cesium inventory by 2 orders of magnitude and not exceed the waste disposal criteria of the site. Also there remains without any additional strontium or cesium an available loading capacity of 0.23 or 23 percent of the site disposal capacity. The existing nuclide specific waste loading fraction, F_o, for the next shipment is thus 0.77.

Equation B-1 takes advantage of the fact that there are several cells and a relatively large dedicated disposal area to average the loading fraction for the entire site. If however there is only one cell, or if the loading fraction for the site exceeds unity, the disposal site operator must determine an excluded area, A_c, to surround the waste cell, or to provide an expanded dedicated area for the site, such that the average concentration of the site is not exceeded. This condition and the criterion given by Equation B-1 is satisfied as indicated by the fact $F_s \leq 1$. To determine the required excluded area (buffer zone) simply set Equation B-1 equal to 1 and substitute the dedicated site area, A_s, with the excluded area for a single cell, A_c, as follows:

$$1 = \frac{1}{A_c} \sum_{i}^{n} \frac{Q_i}{ACL_i} \qquad \text{(B-2)}$$

where

A_c = The required excluded area or buffer zone surrounding the waste disposal cell or site

Q_i = The waste inventory as defined before

ACL_i = The nuclide specific area disposal concentration limit as defined before

i = The summation index for each nuclide in Table B-1

n = The number of nuclides listed in Table B-1 (i.e. 24)

The excluded area radius (assuming cylindrical geometry), R_c, is determined from Equation B-3:

$$R_c = \sqrt{\frac{1}{\pi} \sum_{i}^{n} \frac{Q_i}{ACL_i}} \qquad \text{(B-3)}$$

For the example of Sr-90 and Cs-137 given previously, if there were only 1 cell, the excluded area radius would be calculated as follows:

$$R_C = \sqrt{\frac{1}{\pi}\left[\frac{100,000}{36} + \frac{100,000}{12,000}\right]}$$

$$R_C = \sqrt{887} \cong 30 \text{ meters}$$

The above criteria, equations and examples represent most of the situations that are likely to confront a waste disposal site operator. Application of these criteria and examples can facilitate safe disposal site operation and assure the safe disposal of radioactive wastes for the long term.

GLOSSARY

Activity (Nuclear)	Radioactivity or the presence of radioactive materials. A measure of the rate at which a material is emitting radiation. 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).
Alpha (α) Radiation	An emission of particles (helium nuclei) from a material undergoing nuclear transformation. The particles have a nuclear mass number of four and a charge of plus two. Alpha radiation is the least penetrating radiation and is stopped by a few centimeters of air or a piece of paper.
Aquifer	A subsurface formation containing sufficient saturated permeable material to yield significant quantities of water.
Background Radiation	The level of radioactivity in an area, which is produced by sources other than the contaminated waste of interest. The background radiation is produced by naturally occurring radioactive materials in the crust of the earth, cosmic radiation and the fallout from nuclear weapons tests.
Beta (β) Radiation	Charged particles (electrons and positrons) emitted from the nucleus of atoms undergoing nuclear transformation. Beta radiation is intermediate in penetration and travels up to 3 m in air; stopped by a thin sheet of aluminum.
Biota	The plant and animal life of a region.
Biotic	Caused by living organisms.

Burial Ground	A location which is dedicated to the subsurface storage or disposal of solid radioactive waste or excess materials.
CFR	Code of Federal Regulations, subdivided by titles and parts, available from U.S. Government Printing Office, Washington, D.C.
Contamination	Unwanted radioactive material, frequently rather finely divided, affecting otherwise usable materials or areas. Radioactive contamination may penetrate into inaccessible areas of equipment, making such equipment too radioactive to use. This equipment then becomes radioactive waste.

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;
	millicurie (mCi) = 10^{-3} curie;
	microcurie (µCi) = 10^{-6} curie;
	nanocurie (nCi) = 10^{-9} curie;
	picocurie (pCi) = 10^{-12} curie;
	femtocurie (fCi) = 10^{-15} curie.

Disposal	To place waste in isolation, with no expectation of retrieval, with adequate protection barriers for the time required to decay to innocuous radioactivity levels.
Dose	A general term indicating the amount of energy absorbed from incident radiation by a specified mass.
Drum	A metal or composition cylindrical container used for the transportation, storage, and disposal of waste materials.
Dry Waste	Radioactive waste material containing no free liquids. Comprised mainly of such materials as rags, paper, clothing, floor sweepings, and plastic film. May also include industrial waste material.
Exposure	The condition of being made subject to the action of radiation.

Fission (Nuclear)	The division of a nucleus into two nuclides of lower mass, usually accompanied by the expulsion of gamma rays and neutrons.
Fission Products	The nuclides formed by the division of a heavier nucleus; usually in a nuclear reactor.
g	Abbreviation for grams
gal	gallons
g/l	grams per liter
Gamma (γ) Radiation	High-energy, short wavelength electromagnetic energy emitted during a nuclear transition. Gamma radiation is the most penetrating radiation.
GCD	See Greater Confinement Disposal.
GCDF	Greater Confinement Disposal Facility.
Greater Confinement Disposal	Emplacement of low-level radioactive waste, (typically having high-specific-activity, HSA, or long-lived nuclides), with no expectation of retrieval, within the soil at sufficient depth, usually greater than 10 meters, that it is very unlikely to be disturbed by plant roots, burrowing animals, or inadvertent human reclaimer activities, including such normal activities as home building, farming, etc.
Groundwater	Water which exists or flows below the surface (within the zone of saturation).
Half-Life	The time required for the activity of a radionuclide to decay to half its value. Half-life is used as a measure of the persistence of radioactive materials and each radionuclide has a characteristic constant half-life.
Hazard	A circumstance which could produce an undesirable health or safety impact.

High-Level Waste	As defined by NRC, high-level waste includes processed and unprocessed spent fuel and aqueous waste resulting from the operation of the first cycle of the solvent extraction system (raffinate) in a facility for reprocessing reactor fuels.
High Specific-Activity Waste	Waste material with activity levels not meeting the criteria of low specific-activity waste.
Innocuous	Concentration levels of radionuclides which may be considered effectively "non-radioactive" because the toxicity to man has decreased due to decay, or the level of contamination is so low that the material could be discarded without restrictions.
Institutional Controls	Regulation of access to an area by use of statutory laws, operating procedures, security forces, fences, warning signs, barricades, or other types of restrictions.
Intermediate Depth Burial	See Greater Confinement Disposal.
Isotope	Nuclides with the same atomic number (i.e., the same chemical element) but with different atomic masses. Although chemical properties are the same, radioactive and nuclear properties may be quite different for each isotope of an element.
km	Kilometers (1 kilometer = 1000 meters or 0.621 mile).
Low-Level Waste	Radioactive contaminated waste which is not defined by NRC to be high-level waste or by DOE to be transuranic waste, and not including uranium mill tailings.
Low Specific-Activity Waste	Includes alpha emitting radionuclides of the uranium and thorium decay chain having less than 0.1 nCi/gm of activity, or tritium oxide in

	aqueous solution having less than 5 millicuries/liter activity.
m	(1) Meter; (2) as prefix, milli. See "milli."
manrem	The total radiation dose commitment to a given population group; the sum of the individual doses received by a population segment.
meq	Milliequivalent or 1/1000 of an equivalent; an equivalent is that weight of an element which will combine with or displace one atomic weight of hydrogen or any other element of the same combining capacity, such as chlorine.
mg	Milligrams.
micro (μ)	Prefix indicating one millionth (1 microgram = 1/1,000,000 of a gram, or 10^{-6} gram).
milli	Prefix indicating one thousandth (1 milli = 1/1000 of a rem, or 10^{-3} rem).
millirem	One thousandth of a rem. Abbreviated as mrem.
Monitoring	Periodic or continuous determination of quantifiable releases of specific material, such as radionuclides, from a particular site. Also measuring rate of radioactive decay.
mrem	Millirem.
nano	Prefix indicating one thousandth of a micro unit (1 nanocurie = 1/1000 of a microcurie, or 10^{-9} curie).
nCi	Nanocuries.
Neutron	A particle existing in or emitted from the atomic nucleus; it is electrically neutral and has a mass approximately equal to that of a stable hydrogen atom. Neutron radiation is very penetrating.

Nuclide	An atom or a series of atoms having a specific mass, atomic number and nuclear energy state.
Pathway	A tangible route whereby nuclear radiation or radioactive substances can be conveyed from their intended location and potentially contact humans.
pico	Prefix indicating one millionth of a micro unit (1 picocurie = 1/1,000,000 of a microcurie or 10^{-12} curie).
Plutonium	A radioactive element with atomic number 94. Its most important isotope is fissionable plutonium-239, produced by neutron irradiation of uranium-238.
Rad	Radiation absorbed dose. The basic unit of absorbed dose of ionizing radiation. One rad is equal to the absorption of 100 ergs of radiation energy per gram of matter.
Radiation (Ionizing)	Particles and electromagnetic energy emitted by nuclear transformations which are capable of producing ions when interacting with matter; gamma rays and alpha and beta particles are primary examples of energy emitted from nuclear waste.
Radiation Dose	The energy absorbed by matter as a result of exposure to radiation. The energy absorbed has the unit "rad," which is equal to 100 ergs of energy absorbed per gram of tissue.
Radiation Dose Equivalent	A measure of the physiological effects of different kinds of radiation on people. It has the unit "rem," and is the product of radiation dose in rads and the quality factor, or relative biological effectiveness factor (RBE), for the particular type of radiation. (For X-rays, gamma (γ) rays and most beta (β) particles, RBE = 1; for higher energy β particles, RBE $\cong$ 2;

	for alpha (α) particles, RBE $\cong$ 20.) (See also "Rem.")
Radioactivity	A property of some materials whereby high-energy particles and/or electromagnetic waves are emitted from the atomic nucleus.
Radionuclide	A nuclide which is radioactive.
Reclaimer	Any unauthorized person who inadvertently intrudes into a waste site and disturbs or removes the waste. A reclaimer could be involved in such normal pursuits as farming, home building, rock hounding, camping, manufacturing, etc., but not mining or drilling. It is assumed that the act of mining or drilling would involve the use of such equipment as to identify the buried waste material as hazardous.
Rem	A unit of measure for the dose of ionizing radiation which gives the same biological effect as one roentgen of X-rays; one rem approximately equals one rad for X-ray, gamma, or beta radiation. A dose rate is that amount of radiation absorbed in a unit time of one hour. (See "Radiation Dose.")
Retrieval	The process of removing all radioactive contaminated material from a storage site.
Scenario	A particular chain of hypothetical circumstances that could, in principle, release radioactivity.
Shallow Land Burial	Emplacement of low-level radioactive waste in trenches or pits in the soil with a shallow covering usually in the range of one to three meters. Shallow land burial sites may include both permanently disposed waste and retrievable waste.
Shallow-Rooting	Plants whose roots remain within 1 m of the surface.
SLB	Abbreviation for Shallow Land Burial.

Specific Activity	The radioactivity per unit mass (i.e., Ci/gram) of a pure radionuclide or isotope. See "Low Specific-Activity Waste."
Stabilization	The act of placing barriers which prevent or retard waste migration into the biosphere.
Storage	A non-permanent emplacement of radioactive waste in a location with the eventual option of retrieval and disposal.
Transuranic	Nuclides having an atomic number greater than that of uranium (i.e., greater than 92).
Transuranic Waste	Radioactive DOE waste (primarily alpha emitters) contaminated by transuranic (TRU) radionuclides, or waste which contains more than 10 nanocuries/gram of U-233, or nuclides of atomic numbers greater than 92 (i.e., Np, Pu, Am, Cm, Bk).
Tritium	A radioactive isotope of hydrogen with two neutrons and one proton in the nucleus. It is heavier than deuterium (heavy hydrogen). Tritium (T or ^3H) is used in industrial thickness gauges, as a label in tracer experiments, in controlled nuclear fusion experiments, and in thermonuclear weapons. It is produced primarily by neutron irradiation of lithium-6.
TRU	Abbreviation for Transuranic.
Uranium	A naturally radioactive element with the atomic number 92 and an atomic weight of approximately 238. The two principal naturally occurring isotopes are the fissionable uranium-235 (0.7% of natural uranium) and the fertile uranium-238 (99.3% of natural uranium).
Vadose Zone	Related to unsaturated areas of the earth's crust above the permanent groundwater level.

Water Table	Upper boundary of an unconfined aquifer surface below which saturated groundwater occurs; defined by the levels at which water stands in wells that barely penetrate the aquifer.
µ	mu, a prefix. Same as "micro."

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