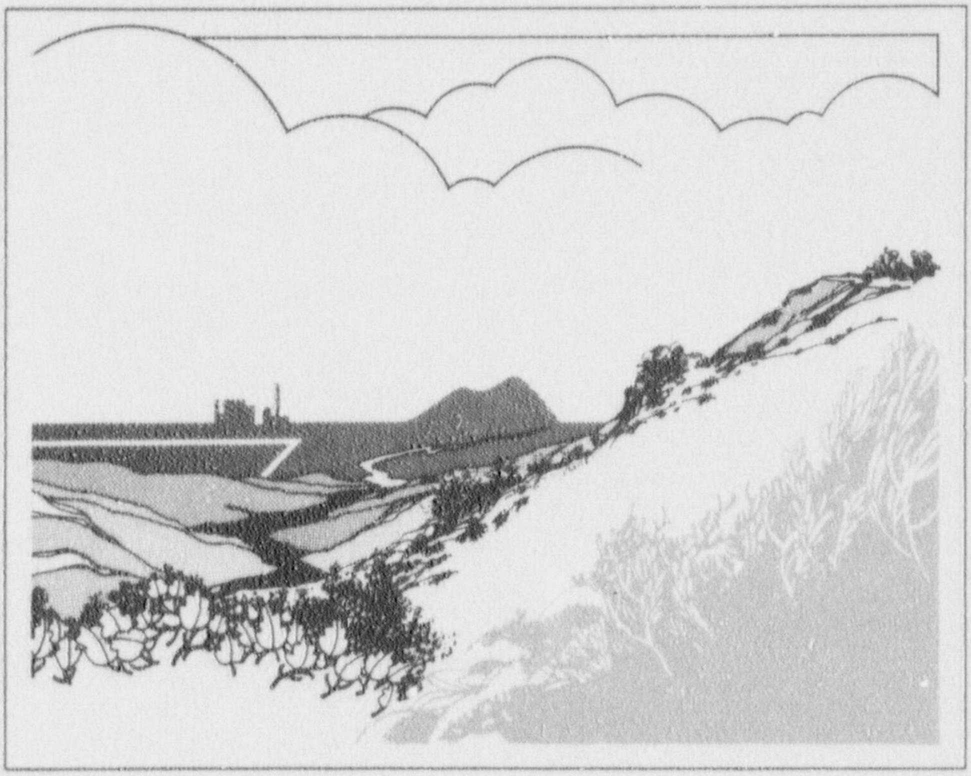
NUREG/CR-4701 Vol. 2
EGG-2465
September 1987

Safety Assessment of Alternatives to Shallow-Land Burial of Low-Level Radioactive Waste

Volume II: Environmental Conditions Affecting Reliability of Engineered Barriers

Fred Cerven
Mark D. Otis

FORMAL REPORT



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Work performed under DOE Contract No. DE-AC07-76ID01570

for the **U.S. Nuclear Regulatory Commission**

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NUREG/CR-4701 Vol. 2
EGG-2465
Distribution Category: RW and CC

SAFETY ASSESSMENT OF ALTERNATIVES TO SHALLOW-LAND BURIAL OF LOW-LEVEL RADIOACTIVE WASTE

VOLUME II: ENVIRONMENTAL CONDITIONS AFFECTING RELIABILITY OF ENGINEERED BARRIERS

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Published September 1987

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Idaho Falls, Idaho 83415

Prepared for the
U.S. Nuclear Regulatory Commission
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Under DOE Contract No. DE-AC07-76ID01570
FIN No. A6845-7

ABSTRACT

The need for new disposal capacity for low-level radioactive waste (LLW) has led to a re-examination of disposal practices. A number of enhancements and alternatives to traditional shallow-land burial have been proposed to meet the need for new capacity and to address various concerns about the performance history of existing commercial LLW sites.

This document builds on the results of the Volume I effort, which identified the important LLW disposal facility engineered barriers of cover and structure. Fifteen potentially important degradation mechanisms for a LLW facility are identified, categorized, and analyzed to determine their importance to the proper functioning of the disposal facility over its 500-year lifetime. Wind storms, biological intrusion, mechanical settling, freeze/thaw cycling, chemical degradation, wind erosion, and water erosion were considered the most important mechanisms. Data supporting concrete structure long-term performance in sulfate environments and long-term cover performance in erosive and biological intrusion environments were obtained. Research on the performance of covers and concrete structures in the presence of the other listed degradation mechanisms is recommended.

FIN No. A6845-7
Office of Nuclear Regulatory Research

EXECUTIVE SUMMARY

The need for new disposal capacity for low-level radioactive waste (LLW) has led to a re-examination of disposal practices. A number of enhancements and alternatives to traditional shallow-land burial have been proposed to meet the need for new capacity and to address various concerns about the performance history of existing commercial LLW sites.

In addition to traditional shallow-land burial and enhanced alternatives referred to as improved shallow-land burial, there are five major alternative near-surface disposal concepts: aboveground vaults, earth mounded concrete bunker tumuli, belowground vaults, augered hole shaft disposal, and mined cavities. It has been established that all of these could be licensed under 10 CFR 61; however, disposal in mined cavities may necessitate additional technical requirements. For this reason, and because of technical difficulties in treating mined cavities consistently with the other alternatives, mined cavities are reviewed here only for the sake of completeness.

The Volume I failure analysis indicated that the cover component of any near-surface disposal system is one of the most important engineered barriers, regardless of the presence of other components such as vaults and enhanced containers. However, structures such as vaults can provide significant enhancement of disposal systems, particularly where they reduce reliance on cover for preventing radionuclide release, inadvertent intrusion, or loss of stability.

The analysis in this report (Volume II) concentrates on the environmental conditions that influence cover and structure reliabilty.

An approach for addressing the reliability of engineered barriers is presented based on the results of previous work which identified earthen covers and concrete structures as the most important categories of engineered barrier. The primary measure of reliability is taken to be the performance lifetime or average time to failure of engineered barriers. A major emphasis is placed on the environmental conditions that promote failure by various mechanisms. The purpose is to identify those environmental conditions which most limit the performance lifetime, and therefore the reliability, of engineered barriers.

One key to addressing reliability is a clear understanding of what is meant by failure. This analysis attempts to define failure in terms of physically measurable quantities that can be used as a basis for the development of engineered design specifications. It is important to note that, while the definitions of failure are based on the performance objectives of 10 CFR 61, they are to be applied to the engineered barriers, not to the disposal facility. Therefore, failure of individual barriers does not necessarily imply failure of the entire facility.

Two major categories of failure mechanisms have been identified, each of which can be promoted by a variety of environmental conditions. One category includes continuous processes such as erosion of covers or chemical attacks on concrete. The other includes discrete events such as floods and earthquakes. The fundamental differences between these two categories determine the nature of the data needed to estimate the mean time to failure due to each.

Engineered barriers need not, and cannot in principle, function forever. Fortunately, the hazard due to failure is closely associated with the toxicity of the waste inventory, which declines as time passes. This consideration has allowed screening of both discrete events and continuous processes to determine which most limit the reliability of engineered barriers over the relevant time period.

The results of this screening analysis indicate that adequate data currently exist to allow designers to accommodate the degradation mechanisms of concern for covers.

- Cover consolidation/subsidence
- Freeze/thaw of the moisture in the soil
- Water erosion
- Wind erosion
- Biological intrusion.

Utilizing naturally occurring materials, properly compacted, and with adequate vegetation should result in a properly performing cover component for a LLW disposal facility.

Mechanism interactions can be qualitatively identified. The strongest interactions are due to mechanical processes generating mechanical settling, and physical damage to concrete engineered barriers due to settling and freeze/thaw cycling enhancement of chemical attack potential. Further investigation is recommended.

Performance data on other engineered barriers, particularly concrete structures (either actual or modeled), are generally lacking for the time frame of interest. Two exceptions are for concrete in a sulfate environment and high-integrity steel containers in high-level and hazardous waste disposal applications. Information on the behavior of these materials in the presence of the other environmental conditions does not extend to the 300- to 500-year time frame of interest. The mechanisms for which data are needed are:

- Biological intrusion
- Mechanical settling
- Freeze/thaw cycling (aboveground vault)
- Chemical degradation (other than sulfate attack).

Some clear guidelines are available concerning the time periods over which data are needed. The desired performance lifetime should be in the time period of 200 to 300 years. The toxicity of low-level waste inventories falls rapidly to very low values over this period and then remains essentially unchanged for a very long time. Designing for periods in excess of 300 years gains very little in terms of reduced hazard.

Having identified the most important failure mechanisms, further quantification of performance lifetime is hampered by limitations in the available data. There are four general observations that can indicate those areas needing further investigation. First, discrete events are generally better understood than continuous processes. Second, failure mechanisms, including continuous processes, are better understood for covers than for concrete structures. Third, failure of concrete is better understood with respect to structural strength than to radionuclide containment. Clearly, more information is needed on continuous degradation of concrete and on its containment properties.

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INTRODUCTION

Background

The need for new disposal capacity for low-level radioactive waste (LLW) has led to a reexamination of current disposal practices. A number of enhancements and alternatives to traditional shallow-land burial have been proposed to meet the need for new capacity and to address various concerns about the performance history of existing commercial LLW sites.[1,2,3,4]

None of these proposed enhancements or alternatives has yet been constructed for use in commercial LLW disposal. Experience with other applications of these disposal technologies is limited and, in some cases, lacking altogether. The purpose of this document is to provide a method for addressing issues affecting the performance of alternative LLW disposal technologies in the absence of performance histories for actual LLW sites. The emphasis is on environmental conditions that tend to promote the failure of earthen covers and structural components such as concrete vaults.

This is a continuation of work previously published as a failure analysis of engineered barriers in low-level-waste disposal.[5] That volume identified the major engineered components of several disposal alternatives and examined the degree to which each alternative depended on these components to fulfill the functions of a disposal facility. The method used took into account the degradation of disposal system function resulting from all combinations of failure among the components of each alternative. The results of the analysis identified which components of the selected alternatives are most important to each of the functions of a near-surface disposal system, ranking them according to their contribution to the performance of each function.

The failure analysis was intended as a screening device for identifying the most important engineered barriers. The objective of the extension of that analysis is to further investigate the mechanisms and rates of failure for these important components. This will provide a technical basis that will assist in developing performance criteria and support the licensing of the design, siting, construction, operation, and closure of alternative methods for the disposal of low-level nuclear waste.

Results of Previous Analyses

The previously published analysis (see Reference 5) addressed five low-level-waste disposal technologies, including traditional shallow-land burial as a point of reference. These were:

- Shallow-land burial (SLB)
- Belowground vaults (BGV)
- Augered holes (AH)
- Earth-mounded concrete bunker (EMCB) tumulus
- Aboveground vaults (AGV).

Various enhancements to each alternative brought the total number of designs examined to ten.

Each disposal facility design was treated as a combination of some or all of four basic engineered components arranged either above or below natural grade. These components were defined as follows:

- Cover—An earthen cap with design features to address 10 CFR 61 requirements for mitigating water infiltration, erosion, and biotic intrusion. (e.g., impervious clay and gravel layers, plastic liners, vegetative cover).

- Structure—A stabilized enclosure, sealed against the movement of water and providing resistance to subsidence or collapse (e.g., a concrete vault or reinforced liner for an augered hole).
- Fill—Any material (e.g., sand, gravel) placed in the interstices of the waste to prevent collapse or subsidence which may provide some structural stability and resistance (e.g., grout, concrete) to movement of water.
- Container—A modular waste receptacle (e.g., high-integrity container, Surepak canister) designed to provide greater structural stability and resistance to movement of water than a standard steel drum or wooden box.

The dependence of each alternative design on its constituent components was examined for six disposal system functions. These functions were derived from the performance objectives of 10 CFR 61 Subpart C.[6] Three functions were aspects of containment of radionuclides by the engineered barriers. These were:

- Prevention of release to atmosphere
- Prevention of release to surface water
- Prevention of release to groundwater.

The remaining three functions were:

- Prevention of inadvertent intrusion
- Minimization of dose to workers
- Maintenance of disposal site stability.

No attempt was made in the failure analysis to compare the relative merits of alternative disposal systems. What was provided, however, was a framework for discussing the contributions of individual components to system performance and a point of departure for future reliability studies.

The method used was found to be most directly applicable to the system functions that relate to containment of radionuclides and maintenance of stability. A weaker relationship exists between this method and the system function of minimizing worker exposure to radiation. This is because occupational radiation protection depends on factors other than design of the engineered components of a disposal system. Operational practices in particular are critically important.

The results of the failure analysis indicate that the cover component of any near-surface disposal system is one of the most important engineered barriers. This is true for all disposal system functions. Regardless of the inclusion of other engineered barriers, careful consideration should be given to design, construction, and maintenance of covers.

Structures such as vaults can provide significant enhancement to near-surface disposal systems, particularly where they reduce reliance on cover for preventing radionuclide releases, inadvertent intrusion, and loss of stability.

Fill is necessary for ensuring stability of the cover, particularly in shallow-land burial and EMCB designs. In general, however, fill does not contribute directly to the performance of other system functions.

This reliability study will focus on potential failure mechanisms of cover and structure. The system functions of primary interest will be containment of radionuclides and maintenance of structural stability. The results of the failure analysis will be combined with the outcome of the reliability study to provide a basis for performing a consequence analysis of failure mechanisms.

FAILURE OF ENGINEERED BARRIERS

General Considerations

The previous study identified the most important engineered components of various alternative disposal system designs. This study will identify the most important environmental conditions which degrade the performance of those components. Before addressing specific environmental mechanisms of failure and their influence on the performance lifetime of low-level-waste disposal units, concepts which will clarify the discussion of environmental conditions will be introduced.

The following sections will: (a) provide a working definition of failure for engineered barriers; (b) categorize the major types of failure mechanisms; (c) introduce the concepts of probability of occurrence and probability of failure; and (d) discuss the consequences of failure as a function of time following closure of a disposal facility. These ideas will be used to evaluate specific influences on the performance of engineered barriers.

Definitions of Failure

In order to address the effect of various environmental conditions on the performance lifetime of engineered barriers, it is necessary to have a well formulated definition of failure for those barriers. This analysis is concerned with two disposal facility functions: containment of radioactivity and maintenance of structural stability. No single definition of failure can adequately treat both of these functions. It is possible, for example, for a concrete structure to retain sufficient strength for purposes of stability while losing the capacity for radionuclide containment through cracking.

There are two primary requirements of a definition of failure. First, it must be based on physically measurable quantities. This is necessary for quantifying performance lifetimes, designing experiments to measure the effects of environmental conditions, and deriving engineering criteria for engineered barriers.

Secondly, a useful definition of failure must also be based on the performance objectives of 10 CFR 61. These performance objectives are intended to apply to low-level radioactive-waste disposal facilities which are composed of individual disposal units. Disposal units may or may not include various engineered barriers in their design. It is possible for any individual disposal unit or engineered barrier to cease functioning without causing the failure of the entire disposal facility. For example, 10 CFR 61 requires that doses to the general public not exceed 25 mrem/yr from the disposal facility. Loss of radionuclide containment from a single disposal unit may contribute some small fraction of that limit. Under these conditions, one engineered barrier of a disposal unit may have "failed" while the disposal facility as a whole has not.

These considerations require a clear distinction between failure of an engineered barrier and failure of the entire disposal facility. The proposed definitions used for this discussion are summarized below in the Screening Analysis. Other criteria could be developed along similar lines if other aspects of engineered barrier performance are to be addressed.

Criteria for failure of the entire disposal facility are based on 10 CFR 61 in a manner consistent with the previous failure analysis (see Reference 5). These criteria are not directly measurable quantities. The dose to the general public is estimated using a complex performance assessment model that includes many factors besides engineered barrier performance. The need for active maintenance is an operational criterion without quantitative definition.

Criteria for failure of engineered barriers are based on measurable quantities that indicate the degree to which each function can be performed. The definition of an engineered barrier given in 10 CFR 61 is "a manmade structure or device that improves the disposal facility's ability to meet the performance objectives." With respect to containment, this means that resistance to radionuclide movement greater than that of the surrounding geologic medium alone is required for a functioning engineered barrier. The effective permeability to water (diffusion plus bulk flow) is proposed as a measure of this property. With respect to stability, loss of structured strength equivalent to the safety factor is proposed for two reasons. First, even with reasonable design safety factors, such a loss indicates that subsidence or collapse is imminent. Second, a useful body of data on important environmental conditions already exists using this measure.

Failure Mechanisms

Environmental conditions that degrade the performance of engineered barriers can be classified into two major categories according to the way in which they promote failure. These are discrete events and continuous processes. The fundamental differences can be seen in their effects over time, their probabilities of occurrence, and the kind and availability of data to describe them.

Discrete events include those conditions which can cause failure at a single point in time, without any prior effects on the disposal system. Examples include floods and seismic events. Such events are typically assumed to occur randomly with equal likelihood in any given time period.

Data estimating the likelihood of such events are commonly expressed as annual probabilities. For events of variable magnitude, such as flooding, a design basis event that has a unit probability over some time period is chosen. A "500-year" flood, for example, is assumed to have a uniform probability of occurrence over time.

For the purposes of this analysis a recurrence interval derived from the 500-year performance lifetime, specified by 10 CFR 61 has been assumed. More stringent technical requirements may be suggested by future guidance. However, this will not affect the methodology used in this report.

When designing engineered barriers, it is common practice to choose a reoccurrence interval of the design basis event. Site characterization data are then analyzed to determine the magnitude of the event corresponding to that interval. Thus, the size of the 500-year flood is site-specific, while the annual probability of occurrence is a site-independent constant.

Continuous processes are those conditions in which damage to the engineered barrier accumulates over a prolonged period, performance progressively degrades, but failure is not manifest until sufficient damage occurs. Examples include erosion of earthen covers and chemical attacks on concrete structures. Such processes have a probability of either zero or one. That is, for given site conditions, they either operate or they do not. If a continuous process of degradation is operating, the most important concern then becomes the rate at which damage is accumulating.

Data on continuous processes vary widely in quality. Some processes, such as erosion, are fairly well understood. Others, particularly those affecting the containment properties of concrete, are known to occur, but information on rates of degradation is limited. It is known, however, that rates will vary widely on a site-specific basis. For most processes, parameters that can characterize a site environment as severe or benign, with respect to that particular failure mechanism, are available.

Not all of the above mechanisms can occur simultaneously at a single site. The occurrence of both discrete events and continuous processes depends on a variety of site characteristics. Two examples of different site characteristics are a wet eastern site and a dry western site.[6] Table 1 provides a comparison of the characteristics of each. Further detail would be required to address the occurrence of all possible mechanisms of degradation for any specific site.

Probabilities and Consequences of Failure

The two distinct categories for mechanisms of failure have been characterized in terms of their probabilities of occurrence. It is also important to describe the relation between the occurrence of an environmental condition and the resulting failure of an engineered barrier.

For discrete events, it will be assumed that the barrier fails at the time of occurrence. This is primarily a result of the choice of a design basis event in the engineering of the facility. If, for example, a 500-year recurrence interval is chosen for the design basis flood, it will be assumed that any flood equal to, or greater than, that magnitude will result in failure. In addition, it will be assumed that events greater than design basis will occur with a frequency only slightly less than the design basis, i.e., 2×10^{-3} per year for the 500-year flood.

For continuous processes, the relation between probabilities of occurrence and failure is fundamentally different. If environmental conditions are appropriate for a given process, it will occur. However, failure will result only after sufficient degradation has taken place. Thus, the annual probability of failure will be zero until some point determined by the rate of degradation. Uncertainties in the process will result in a distribution of values around the mean time of failure.

These distinctions are illustrated by the curves presented in Figures 1 and 2. For discrete events, the annual probability of failure (POF) is constant and small. Integrating over the design basis interval gives a cumulative POF of one. For continuous processes, the annual POF is zero until sufficient damage accumulates, after which the annual POF can become large. Integrating over the distribution of values about the mean failure time gives a cumulative POF of one.

The potential consequences of failure depend on when failure occurs. For containment of

Table 1. Typical eastern and western site characteristics

Natural Site Features	Units	Eastern Site	Western Site
Depth to aquifer	ft	92	450
Soil porosity	—	.48	.25 to .50
Surface soil bulk density	lb/ft^3	87	110
Sub-trench vertical velocity	ft/yr	4.4	$6x10^{-5}$
Average soil density	lb/ft^3	100	108
Soil pH	pH	<5	8
Groundwater Cl	mg/l	N/A	200
Groundwater SO_4	ppm	N/A	60 to 2300
Average wind speed	mi/hr	11	11
Annual precipitation	in/yr	40	9
Soil moisture content	%	>50	<17

Assumed Structural Conditions

Characteristic	Units	Eastern Site	Western Site
Disposal unit service life	yrs	500 yrs	500 yrs
Soil bearing capacity	lb/ft^2	>3500	>2000
Soil weight	lb/ft^3	110	110
Base wind load	mph	70	70
Tornado wind speed	mph	360	360
Earthquake max acceleration	g	0.3	0.3
Backfill compaction	Modified Proctor	>95%	>95%

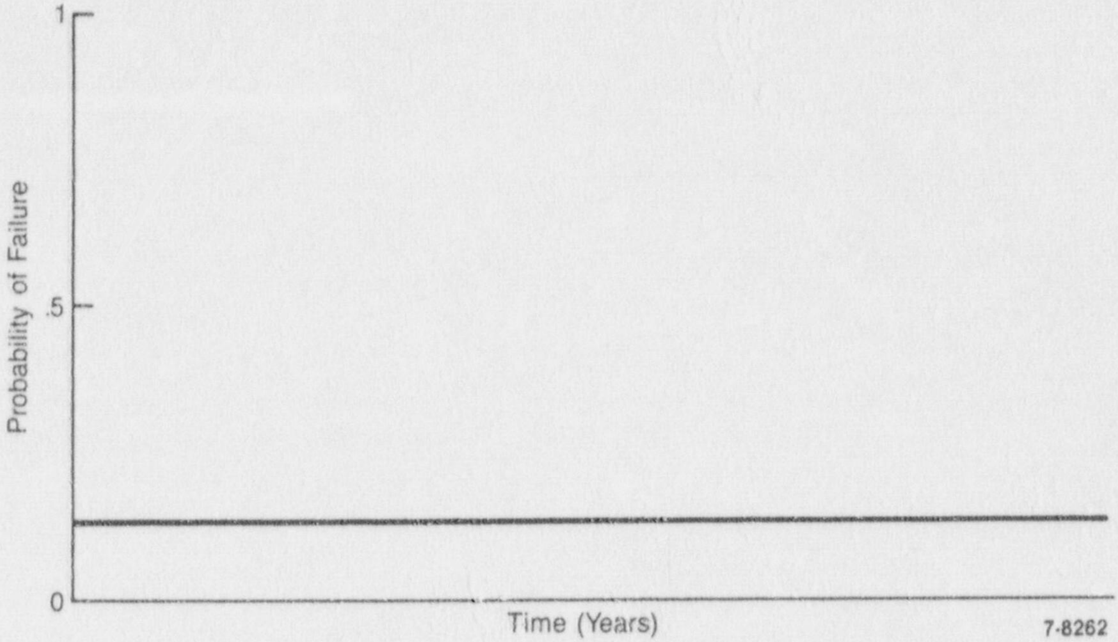

Figure 1. Generalized probability-of-failure curve for discrete event mechanism.

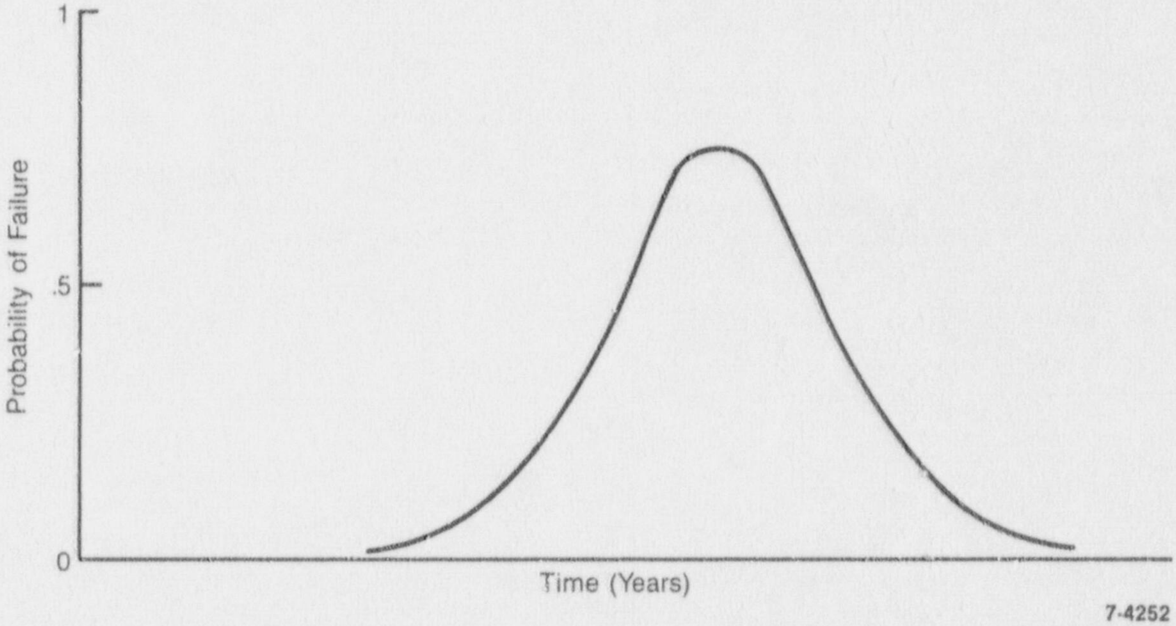

Figure 2. Generalized probability-of-failure curve for continuous mechanism.

radioactivity, the consequences are roughly proportional to the level of hazard associated with the waste inventory. This is illustrated by Figure 3, which plots the normalized radiotoxicity of a typical commercial waste stream over time from the start of operations. Normalized toxicity is the sum of the number of curies of each nuclide weighted by their ingestion dose conversion factors and is a useful measure of total radiological hazard for a mixture of nuclides. The figure depicts a facility with a 30-year operational period, during which waste is emplaced at a constant rate. Following the end of operations, radioactive decay reduces the inventory until, after about 250 years, the hazard levels off at a few percent of maximum. This level persists for several hundred years and is a result of a few very long-lived nuclides, primarily iodine-129, carbon-14, and technecium-99.

A failure at maximum inventory will have greater potential consequences than a failure after several hundred years of radioactive decay. The choice of the design basis reoccurrence interval for discrete events and the mean time to failure for continuous processes can determine the maximum potential risk associated with a given waste stream. If risk is taken to mean the product of the probability of failure and the consequences of failure, then the annual maximum potential risk could be represented by combining the toxicity curve of Figure 3 and the annual POF curves of Figures 1 and 2. This further reinforces the fundamental difference between discrete events and continuous processes. The annual risk from a discrete event will depend entirely on the inventory since the annual probability is constant. If the mean time to failure occurs while inventories are large, the maximum potential risk will also be large. If the mean time to failure occurs after significant radioactive decay, then the maximum potential risk will be small. Additionally, while the annual POF is zero, the annual risk will be zero, regardless of the waste inventory.

Relevant Time Scales

There are considerations, in addition to waste inventory, which vary over the desired performance lifetime of engineered barriers. Regardless of the specific disposal system design, there are several phases in the lifetime of a disposal facility and in the lifetimes of individual disposal units. These result from the sequence of events required by the construction, operation, and management of any facility. Here it is important to distinguish between the facility as a whole and the disposal units within the facility. As shown in Figure 4, the relevant time scales for the facility are approximately 30 years for the operational phase, 1 to 5 years for the post-closure monitoring period, 100 years for institutional control (custodial care), and an additional 400 years for long-term closure. For the disposal unit, there is an approximate one-quarter-year construction period, an approximate two-year waste emplacement period, and then monitored and long-term closure. A disposal unit may be in monitored storage (a type of institutional control) for a large portion of the facility operational period.

The engineered barriers are components of individual disposal units, not of the facility as a whole. The performance lifetime of such barriers begins when waste emplacement ceases and the unit is "closed," which may be long before site closure takes place.

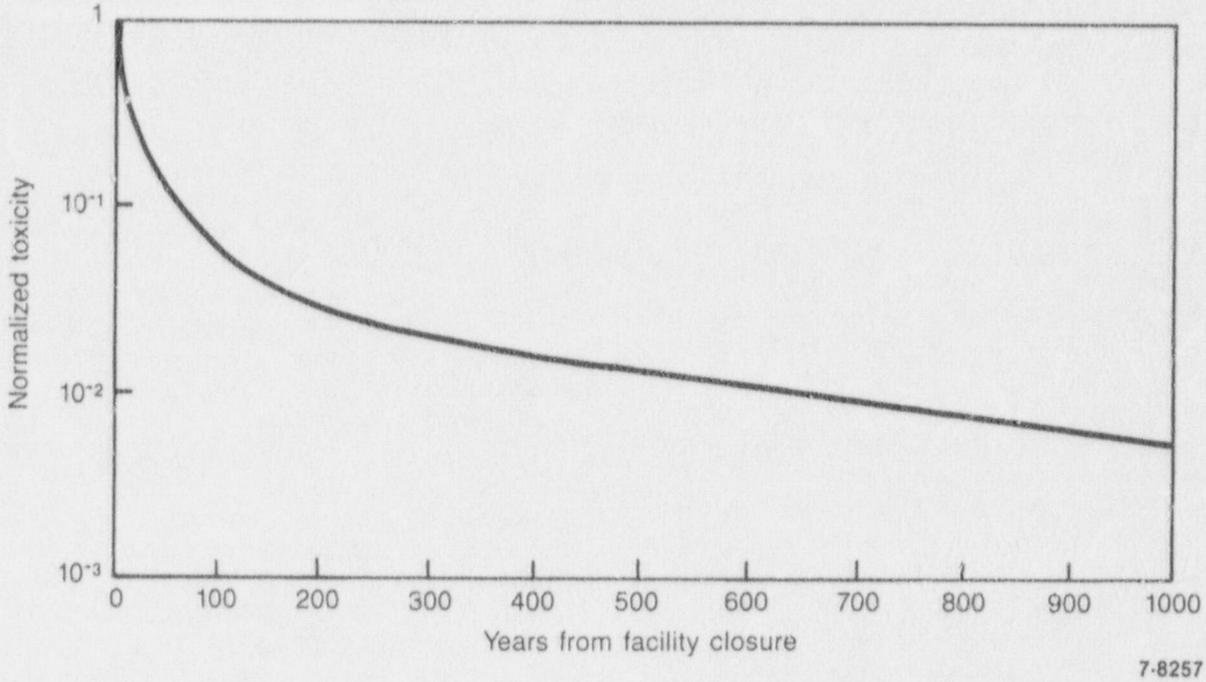

Figure 3. Normalized LLW inventory curve.

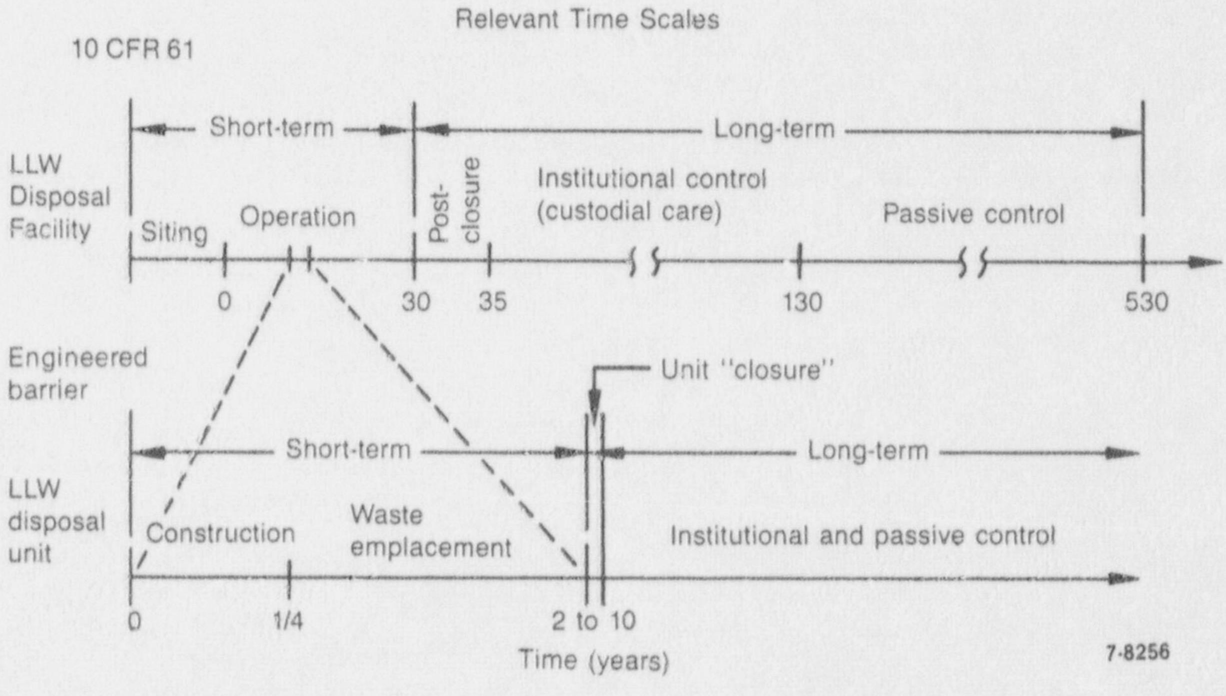

Figure 4. Relevant LLW facility and disposal unit time scales.

ENVIRONMENTAL CONDITIONS PROMOTING FAILURE

Identifying the most important environmental conditions and their effects on unit reliability encompasses a number of logical steps. These are:

- Identifying applicable approaches to reliability analysis
- Identifying site degradation mechanisms
- Defining severe and benign environments with respect to these mechanisms
- Performing a screening analysis to identify the mechanisms of greatest concern
- Gathering and analyzing data on low-level-waste disposal facility (LLWDF) component behavior, given these mechanisms.

With the exception of performing a quantitative reliability analysis, this section presents the rationale used to identify the mechanisms of greatest concern, data available on these failure mechanisms, and reliability information that can be derived from this data.

Approaches to Reliability Analyses

Probabilistic Risk Assessment (PRA) has been used to meet Nuclear Regulatory Commission (NRC) regulatory criteria and standards for reasonable assurance that reactor plant components will perform as required. However, since the performance lifetime estimation of LLWDF components is independent of risk to humans, Probabilistic Reliability Analysis, which is a component of PRA, is the appropriate technique to apply in evaluating the acceptability of LLWDF components. This analysis technique does not provide definitive answers or rigorous solutions in a statistical sense, but does provide an organized approach in evaluating a system or component and provides insight into system weaknesses and strengths.

Probabilistic Reliability Analysis can be performed either qualitatively or quantitatively. The NRC-Reactor Safety Study[7] was based on the Bayesian (qualitative) approach. Qualitative analysis provides valuable insight into identification of the mechanisms that contribute to system *unreliability*. Quantitative analysis utilizes available experience and experimentation data models to provide a numerical value of the probability that a system or component will perform as long as required or, conversely, to estimate the expected time to failure of a component or system.

Given that reliability analyses for LLWDF components must be based on information about the component's performance in similar non-LLW environments, the qualitative approach is pursued here.

Qualitative Reliability Analysis. Qualitative Reliability Analysis can be performed to achieve one or more of the following objectives:

- Identify important system components
- Aid in the systematic assessment of overall system safety
- Document and assess the relative importance of all identified failure mechanisms
- Develop discipline and objectivity on the part of the designer
- Provide a systematic compilation of data as a preliminary step to facilitate quantitative analyses.

Reference 5 provided an assessment of the relative importance of LLWDF components (see first item above). The task addressed in this report provides information on the relative importance of failure mechanisms and gathers available information in preparation for a quantitative analysis. Such information can then be compiled and displayed in a variety of formats to allow evaluation of overall system reliability, identify data gaps, and resolve issues.

The above approach is usually referred to as a failure-mode-and-effect analysis (FMEA).[8] Other qualitative techniques available, but not pursued here, are common-mode-failure analysis (CMFA)[9] and cascade-failure analysis (see Reference 8). They may be appropriate in further work on this subject.

Quantitative Reliability Analysis. Quantitative reliability analysis is performed with the objective of obtaining a numerical value of the probability that the system or component will perform as originally intended. Standard analytical techniques such as ANOVA and Monte Carlo simulation are available as the core methods. These would then provide sensitivity and uncertainty data. Currently, not enough data or models appear available to allow for quantitative analysis. However, qualitative analysis has revealed significant useful data and narrowed the field of significant degradation mechanisms to a reasonable number.

Site Degradation Mechanisms

The relative vulnerability of the components of each disposal unit to the various failure mechanisms depends upon the phase in the lifetime of the unit. For example, a disposal unit which is eventually to be covered with earth would be susceptible to freeze/thaw cycles or fires during the construction and waste emplacement time frames. After these time frames, the unit would be closed, the cover would be in place, and external sources for these events would have been effectively eliminated. On the other hand, once the waste is emplaced and the unit is closed, the vault is subject to long-term mechanisms, such as the effects of soil-related chemical attack for the duration of the site.

These principles are applied to screen possible failure mechanisms in order to identify those of greatest concern and, as a result, for which a more detailed analysis is warranted.

In an earlier section, failure mechanisms were classified as either continuous processes or discrete events. Continuous processes can be further subdivided into those that act over the short term following construction and those that act over the long term.

These categories of failure mechanisms can be applied to both covers and structures, either earthen or manufactured (concrete, steel, etc.). Examples of short-term continuous processes are settling and freeze/thaw exposure. Examples of long-term continuous processes are acid and sulfate attack. Examples of discrete events are floods and earthquakes. Table 2 identifies those mechanisms which are potential major contributors to disposal unit failure. This list is a compilation of those available from a number of sources[10,11] and represents the most likely at any site, regardless of location. Note that the mechanisms fall into four general categories: Discrete natural causes and continuous mechanical, chemical, and special concern processes. Flood, fire, wind storm, and earthquake represent the discrete natural causes; wind erosion, water erosion, biological intrusions, mechanical settling, and freeze/thaw represent mechanical processes; sulfate, acid, chloride, and calcium hydroxide attack/leaching represent chemical processes; radiation and biodegradation effects represent special concerns.

In the Volume 1 failure analysis report (see Reference 5), failure mechanisms included items such as infiltration, subsidence, slope failure, voids, cracking, etc. These are not actual mechanisms, but are the symptoms of a mechanism at work. For example, infiltration is a symptom of failure due to erosion or animal intrusion or a combination of these and others. Table 2 is therefore seen as a clarification of the previous one, in that the distinction between mechanisms and symptoms is realized. Figures 5 through 7 present fault trees which indicate how the possible mechanisms propagate to ultimately result in disposal unit functional loss. Three charts are provided, one each for the covered and uncovered vault designs and a third for the cover component of a LLW facility. Interaction of the various mechanisms would require a cascade mode failure analysis, which is beyond the scope of this document. It can be drawn from the information in the charts that an uncovered vault is susceptible to more degradation mechanisms, for a longer period, than a covered vault. The cover component mitigates some of the mechanisms once it is installed, relieving the vault of that burden.

Site characteristics determine the possible active degradation mechanisms. For example, from the above site characteristics, sulphate attack due to soil/water sulfates is of negligible concern for the typical eastern site. Acid attack, on the other hand, would need to be considered.

Some items considered very important during the construction and waste emplacement time frames are deliberately not considered. These include construction practices, design, and operational practices. It is assumed that deficiencies in these areas can be identified and mitigated through use of good quality assurance practices, frequent inspections, and remedial actions, when necessary, while the unit is open. Only those characteristics not directly related to construction practices, or those having long-term attack mechanisms, will be focused on here. These construction-related characteristics are important, but, because they are adequately addressed in construction standards, are not pursued further here. The American Concrete Institute (ACI), American Society of Mechanical Engineers (ASME), American National Standards Institute (ANSI), Uniform Building Code (UBC), National Electric Code (NEC), and others have developed adequate construction practice requirements for construction-related and some short-term degradation mechanisms.

Severe Versus Benign Environment

The environmental conditions promoting degradation of engineered barriers can occur to greater

Table 2. Potential engineered barrier degradation mechanisms

Mechanism	Definition
Discrete Events	
Flood	Overrunning of the site with water from an external source (such as a dam break or river excursion)
Fire	Fire in waste due to lightning, vehicle spark, or fuel leak
Wind storm	Tornado or other severe wind storm
Earthquake	Seismic activity that generates rolling ground motion at the site
Continuous Processes	
Wind erosion	Removal of cover material due to normally occurring site winds
Water erosion	Removal of cover material due to normally occurring precipitation
Biological intrusion	Animal or vegetation intrusion into the cover
Mechanical settling	Dynamic differential settling due to addition of waste, barrier, and cover
Freeze/thaw	Alternate freezing and thawing cycles that could result in stress-induced cracking or cement paste structural disruption
Sulfate attack	Waterborne soluble salt attack of cement paste constituents
Acid attack	Acidic water in contact with concrete attacks paste constituents
Chloride attack	Seawater, brackish groundwater or airborne salt compounds leaching paste components from concrete
$Ca(OH)_2$ leaching	Lime removal from cement paste by water
Radiation	Degradation (altering) of concrete paste constituents
Biodegradation	Metabolic attack of structural components by soil organisms

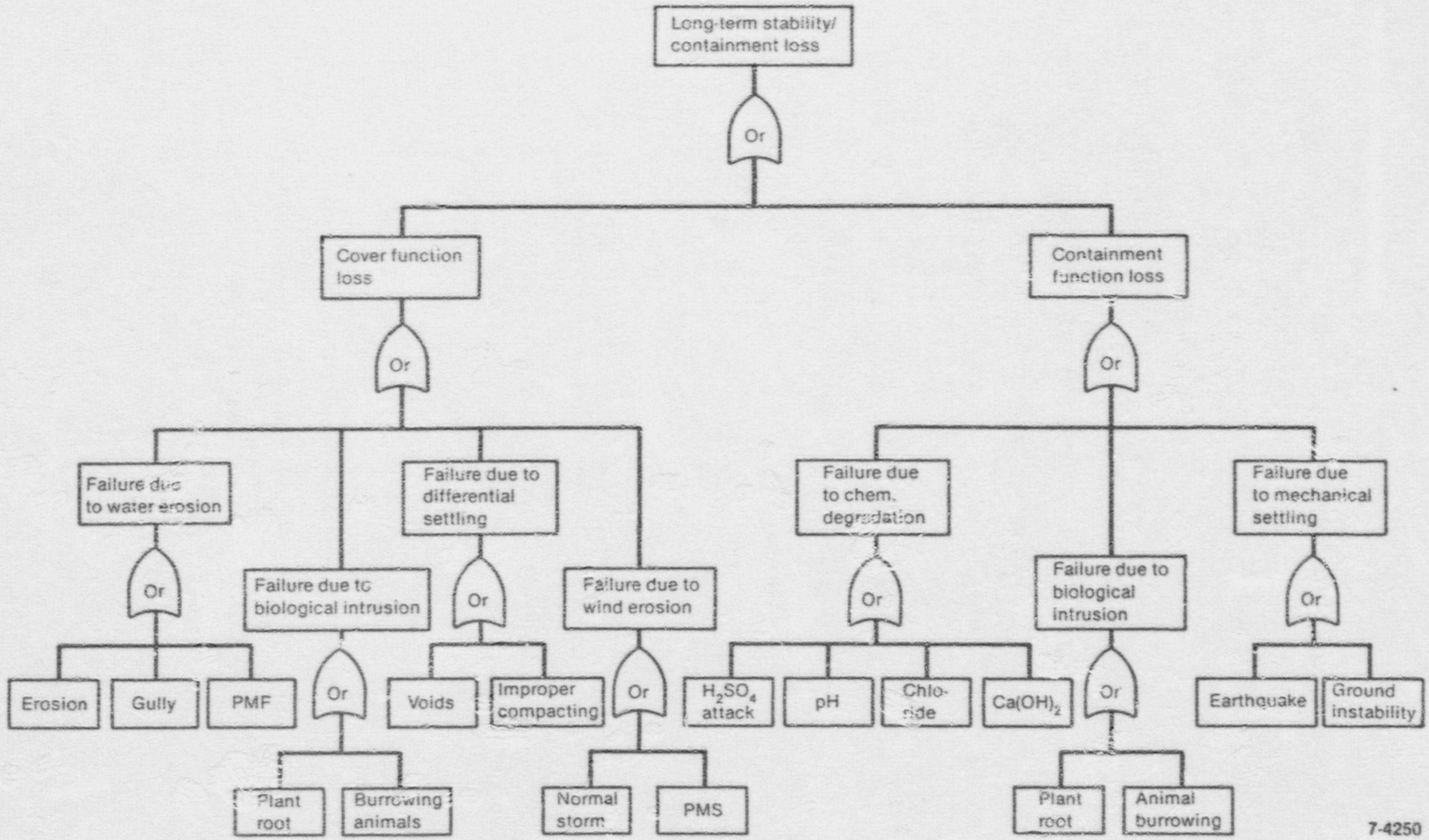

Figure 5. Long-term belowgrade vault (BGV), EMCB, and augered hole (AH) fault tree.

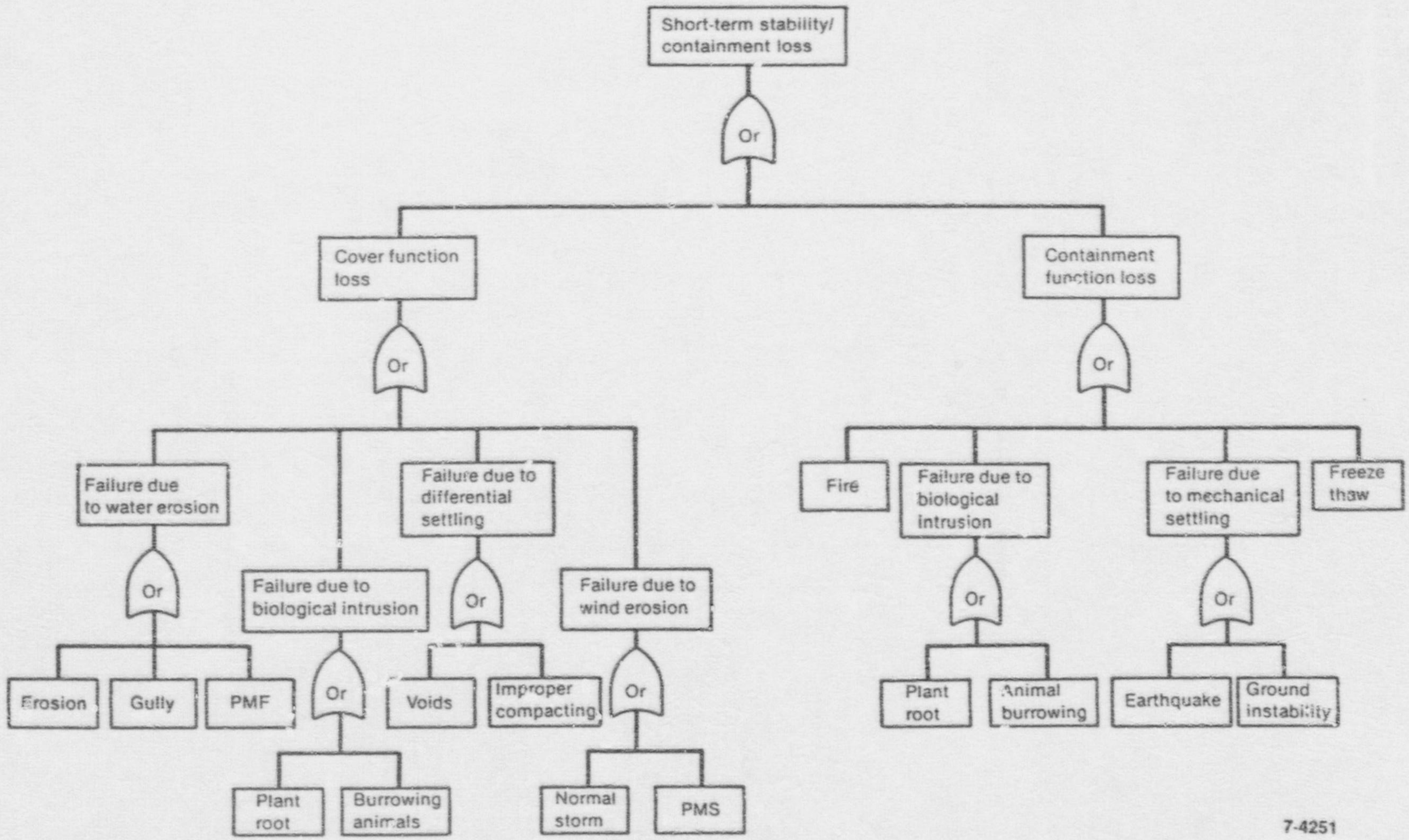

Figure 6. Short-term belowgrade vault (BGV), EMCB, and augered hole (AH) fault tree.

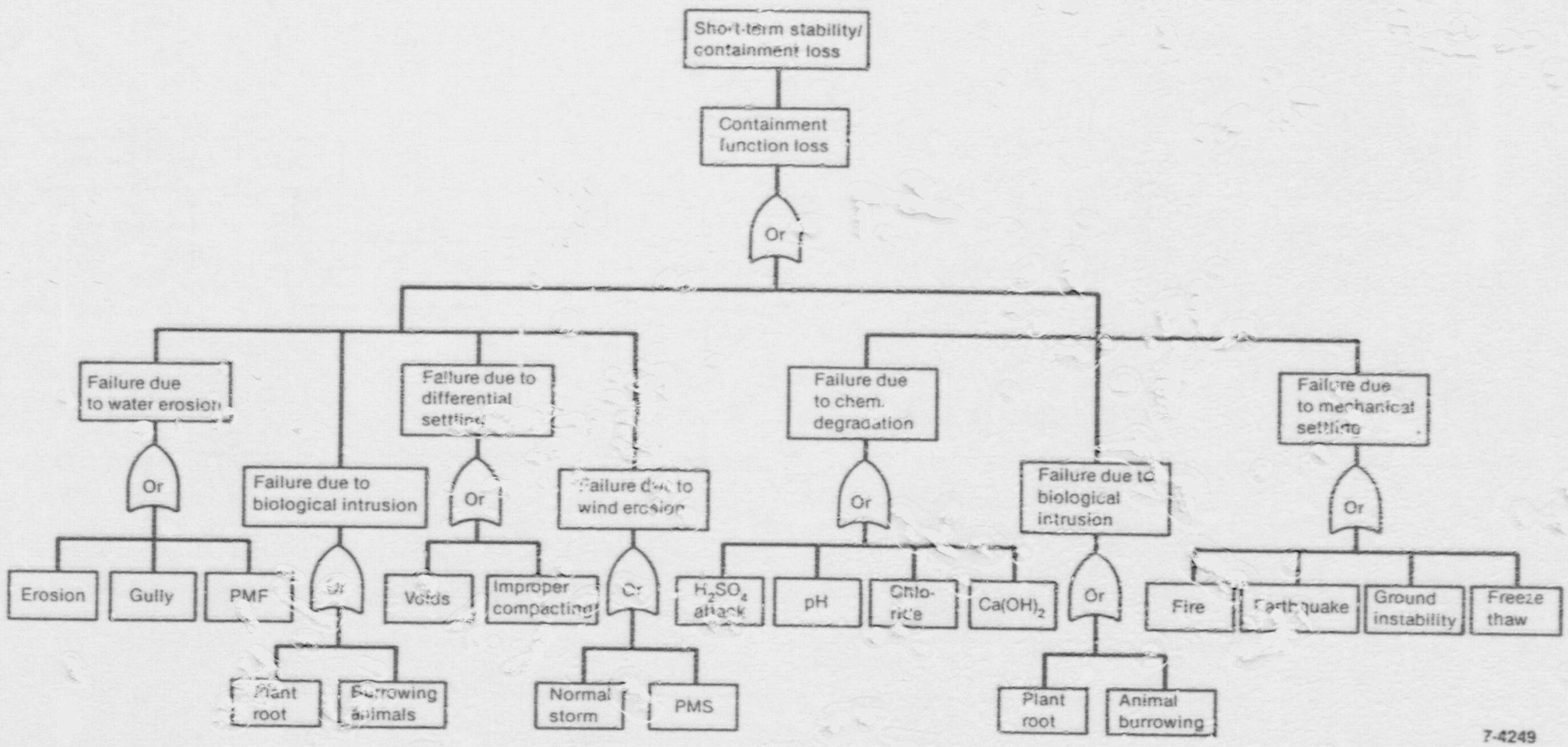

Figure 7. Short-term abovegrade vault fault tree.

of lesser degree at any location. Our concern is with conditions that threaten performance in the desired lifetime of a disposal unit. Any condition that does not threaten performance may be taken to represent a benign environment with respect to that failure mechanism. A severe environment (for a specific environmental condition) is one which could reasonably be expected to cause a disposal unit or one of its major components (engineered barriers) to fail within the required 500-year lifetime of the unit. Examples of such environmental conditions are: soil pH and other chemical characteristics, site climatic characteristics, and site seismicity. These conditions generate failure mechanisms such as acid attack, freeze/thaw cycling, and earthquakes respectively. Severe environmental conditions would, in most cases, be site specific and usually exceed the normally expected, and designed for, conditions at that site. Design considerations can affect the level considered to be "severe." For example, the sulfate concentration that seriously threatens the performance of ordinary concrete may constitute a benign condition if sulfate-resistant concrete is used.

Regulations in 10 CFR 61 require that a one-year site characterization be conducted. The probability that actual conditions will vary from those encountered during this year are high, and local conditions at a nearby site may vary significantly from those at the characterized site. Environmental conditions worse than those observed are likely. Table 3 identifies discrete environmental mechanisms and provides values when they are not site specific. Table 4 identifies continuous mechanisms. Note again that not all mechanisms and conditions are possible at a single site. Rather, the information in these tables comprises a compilation of mechanisms regardless of site.

Screening Analysis

The screening process to identify important degradation mechanisms over the lifetime of a LLWDF consists of a number of elements. These are:

- Defining LLW unit failure and risk
- Estimating degradation mechanism probability of occurrence and probability of failure
- Identifying time periods over which the mechanism operates
- Identifying the consequence of a failure
- Defining relative risk
- Estimating the relative risk associated with each mechanism.

These elements are then used to evaluate actual data for component performance in varied environments.

Defining LLW Unit Failure and Risk. To determine which ones of these mechanisms have the potential for causing LLW unit failure, "LLW unit failure" and "risk" need to be defined. Failure definitions that provide a performance measure distinction both for this analysis and for development of guidelines to evaluate proposed disposal alternatives need development.

A definition of structural failure for a disposal facility is explicitly provided in 10 CFR 61, but several choices are available for disposal unit engineered barriers. These choices depend on such pragmatic considerations as:

- Available data
- What parameters are practically measurable
- Other specific needs.

The performance objective for the entire facility is provided in 10 CFR 61. However, physically measurable parameters (engineering standards) can be applied only at the disposal unit level.

Given the above rationale, two definitions of structural failure emerge. These are:

- According to 10 CFR 61, a *disposal facility* has failed if it has lost structural stability to such a degree that ongoing active maintenance is required or anticipated during and beyond the institutional control time frame (e.g., widespread subsidence or cover collapse is occurring).
- An *engineered barrier* (disposal unit) has failed if its structural component has lost its design safety factor in load-carrying capability (indicating that subsidence or collapse is imminent) within the desired performance lifetime of the unit.

The design safety factor can be specified in any particular case in terms of physically measurable quantities relating to load bearing capacity. For example, data cited in the section on Structure Component Data in this document use loss of 50% of original strength as an endpoint. This would correspond to a design safety factor of 2.

Table 3. Definitions of severe conditions for discrete event degradation mechanisms

Mechanism	Definition
Flood	Any occurrence of the design basis flood (DBF) (site specific)
Fire	Any fire which results in degradation of the cover/container/structure system
Wind storm	Any occurrence of the design basis wind storm (DBW) (site specific)
Earthquake	Any occurrence of the design basis earthquake (functionality lost) (site specific).

Table 4. Definitions of severe conditions for continuous process degradation mechanisms

Mechanism	Severel Conditions
Wind erosion	Greater than expected over site life (site specific)
Water erosion	Greater-than-expected precipitation over site life (site specific)
Biological intrusion	Any not designed for (site specific)
Mechanical settling	Greater than designed for (site specific)
Freeze/thaw	Greater than 300 cycles (ACI Standard)
Sulfate attack	Typical western soils
Acid attack	pH less than 5 (typical eastern soil)
Chloride attack	Any occurrence (typical western soil)
Calcium hydroxide leaching	Exposure to brackish groundwater or salt water in the soil
Radiation	Greater than 3 x 10^{10} Rad (approximately three orders of magnitude greater than expected at a LLW site)
Biodegradation	Any not designed for

A similar distinction can be made in defining failure with respect to radionuclide containment. In 10 CFR 61, containment failure is defined as follows:

- A *disposal facility* has failed if it no longer meets the performance objective of less than 25 mrem/yr (75 mrem/yr to the thyroid) for a member of the general public.

While the 25 mrem/yr criterion is quantitative, it is not directly measurable. Rather, it is calculated using a complex model which includes many factors besides the engineered barrier. To allow for physical measurement of performance, a measure directly applicable to the engineered barrier is once again needed. This definition, to be applied at the engineered barrier, must indicate that the barrier has failed if it does not improve the land disposal's ability to meet the 10 CFR 61 performance objectives. Therefore:

- An *engineered barrier* has failed if it no longer provides resistance to the movement of radioactive material greater than that of the surrounding geologic medium alone.

The physically measurable parameters relating to this definition include permeability, dispersivity, etc. If these indicate greater resistance to radionuclide migration than the surrounding geological medium, then they are improving the facility.

The Department of Energy (DOE) and the NRC define risk for reactors as the probability of occurrence of an event per year times the consequence of that event. Essentially, the consequence of an event is independent of the time when it occurs. This is reasonable for reactors, since once the fission product inventory is built up due to operation, it represents a relatively constant quantity. Since, at a LLWDF, we are dealing with decaying consequences with time (decay with no production), the definition for risk needs to be modified to account for this decreasing consequence. For this discussion, the following incremental risk definitions for LLWDF are proposed:

- Risk is proportional to the probability of occurrence per year (PO) times the normalized radionuclide inventory (consequence) at the time of failure. Therefore, PO values and time period estimates need to be developed for each degradation mechanism.

The time frame in which a particular degradation mechanism is most likely to cause failure can have a pronounced effect on which one is perceived as having the greatest risk. For example, given the following POF and cumulative POF curves for discrete and continuous degradation mechanisms, for POF:

- Discrete maximum risk = (POF) (Maximum Inventory) = (2×10^{-3}) (1) = $2 \times 10^{-3} = 0.002$
- Continuous maximum risk = (Maximum POF) (Maximum Inventory) = $(0.33)(2 \times 10^{-2}) = 6.6 \times 10^{-3} = 0.0066$

for Cumulative POF:

- Discrete maximum risk = (Maximum Cumulative POF) (Inventory @ end) = (1) $(1 \times 10^{-2}) = 1 \times 10^{-2} = 0.01$
- Continuous maximum risk = (Maximum Cumulative POF) (Inventory @ end) = $(0.7)(1 \times 10^{-2}) = 0.7 \times 10^{-2} = 0.007$.

So, depending on how risk is defined and when continuous events lead to failure, a significant difference in results can be obtained. For example, a discrete but low POF event can pose a greater total risk over the time frame of interest. Incremental risk (yearly POF), however, is higher for the continuous process during the potential failure years.

Probability-of-Occurrence (PO) Estimates. Severe environmental conditions occur with differing probability, depending on site characteristics. However, some generalizations can be drawn on a regional basis concerning the occurrence of both discrete events and continuous processes of degradation. Typical values for eastern and western environments appear in Table 5. These values illustrate major regional differences and provide a basis for screening failure mechanisms. They do not represent the actual characteristics of any particular site. Note the distinct differences in estimated PO among the various types of mechanisms. For discrete mechanisms, data are expressed in probabilities based on the time frame in which each is expected to occur at least once. Continuous processes, on the other hand, can either occur or not occur (1 or 0), depending on the surrounding geological and soil conditions. Some mechanisms are mutually exclusive. For example, at an eastern site away from coastal influences, sulfate and chloride attack are virtually unheard of. On the other hand, attack of concrete by acid is virtually unheard of at

Table 5. Typical probability-of-occurrence estimates for eastern and western sites

Mechanism	Probability of Occurrence per Year: Typical Eastern Site	Typical Western Site
Flood	2×10^{-3}	1×10^{-6}
Fire	1×10^{-3}	1×10^{-3}
Wind storm	5×10^{-1}	1×10^{-1}
Earthquake	2×10^{-6}	2×10^{-6}
Wind erosion	1	1
Water erosion	1	1
Biological intrusion	1	1
Mechanical settling	1	1
Freeze/thaw	1	1
Sulfate attack	N/A	1
Acid attack	1	N/A
Chloride attack	N/A	1
Calcium hydroxide attack	1	1
Radiation	0	0
Biodegradation	1×10^{-6}	1×10^{-6}

N/A = Not applicable

a western site because of the soil alkalinity. With respect to radiation, studies have indicated that expected radiation levels at LLW facilities are at least 3 orders of magnitude below those which cause concrete degradation in the time frame of interest. Therefore, no radiation effects are expected. Biodegradation (due to bacteria, etc.) is poorly understood. The number provided is strictly an estimate.

Time Periods for Probability of Failure. The time periods over which degradation mechanisms operate differ. For the 15 mechanisms cited, the time periods which apply were shown in Tables 6 through 8 for covered structures, uncovered structures, and a cover component.

Consequence. The consequence of a failure due to one of the identified degradation mechanisms is determined by the severity of the breach, the radionuclide inventory available for migration at the time of failure, and the expected migration rate. Here one has to resolve the question of severity at the individual unit level. A conservative assumption for site performance at the unit level (given no data) would be that all units fail simultaneously. A more realistic assumption is that the failure rate is driven by probabilistic considerations and time of construction, and follows a standard distribution. Data indicate probabilistic considerations and time of construction to be the more valid assumptions.

Relative Risk. A relative risk factor for each of the degradation mechanisms can be represented as follows:

Risk $\propto$ POF Inventory. Normalized inventory for a unit (and the site in general) can be represented by the curve shown in Figure 8. The inventory rise portion of the curve follows a standard $1\text{-}e^{-xt}$ buildup configuration, and the decay portion follows a standard e^{-xt} shape. X represents an assumed composite radionuclide inventory and t represents the time. Generalized probability-of-failure curves can be represented as shown in Figures 9 and 10.

For any degradation mechanism, the highest risk is derived by multiplying the largest POF by the inventory at that time. For discrete events, this highest risk occurs at unit closure because that is when the largest inventory exists. For continuous processes, the point of highest risk is dependent on the POF curve characteristics. For the generalized curve identified in Figure 9, the maximum risk occurs at the point of highest POF.

Table 6. Aboveground uncovered vault time periods

Mechanism	Probability of Failure	Time of Maximum POF	Timeframe/Unit
Flood	2×10^{-3}/yr	Linear for life	Lifetime
Fire	1×10^{-3}/yr	Linear for life	Lifetime
Wind storm	5×10^{-1}/yr	Linear for life	Lifetime
Earthquake	2×10^{-6}/yr	Linear for life	Lifetime
Wind erosion		200 years	Lifetime
Water erosion	1	500 years	Lifetime
Biointrusion	1 or 0	100 years	Lifetime
Mechanical settling	1 or 0	2 years	Lifetime
Freeze/thaw	1 or 0	50 years	Lifetime
SO_4 attack	1 or 0	400 years (OPC)	Lifetime
Acid attack	1 or 0	?	Lifetime
Cl attack	1 or 0	?	Lifetime
$Ca(OH)_2$	1 or 0	?	Lifetime
Radiation	1	>500 years	Lifetime
Biodegradation	1 or 0	?	Lifetime

OPC--Ordinary Portland Cement

Table 7. Covered vault time periods

Mechanism	Probability of Failure	Time of Maximum POF	Timeframe/Unit
Flood	2×10^{-3}/yr	Linear for life	Before cover
Fire	1×10^{-3}/yr	Linear for life	Before cover
Wind storm	5×10^{-1}/yr	Linear for life	Before cover
Earthquake	2×10^{-6}/yr	Linear for life	Lifetime
Wind erosion	1	At closure	Before closure
Water erosion	1	At closure	Before cover
Biointrusion	1 or 0	100 years	Before cover
Mechanical settling	1 or 0	2 years	1st 5 yrs
Freeze/thaw	1 or 0	50 years	1st 5 yrs
SO_4 attack	1 or 0	400 yrs (OPC)	Lifetime
Acid attack	1 or 0	?	Lifetime
Cl attack	1 or 0	?	Lifetime
$Ca(OH)_2$	1 or 0	?	Lifetime
Radiation	1	>500 years	Lifetime
Biodegradation	1 or 0	?	Lifetime

N/A = Not applicable

Table 8. Cover component time periods

Mechanism	Probability of Failure	Time of Maximum POF	Timeframe/Unit
Flood	2×10^{-3}/yr	Linear for life	Lifetime
Fire	1×10^{-3}/yr	Linear for life	Lifetime
Storm	5×10^{-1}/yr	Linear for life	Lifetime
Earthquake	2×10^{-6}/yr	Linear for life	Lifetime
Wind erosion	1	200 years	Lifetime
Water erosion	1	500 years	Lifetime
Biointrusion	1	100 years	Lifetime
Mechanical settling	1	2 years	1st 5 years
Freeze/thaw	1	500 years	Lifetime

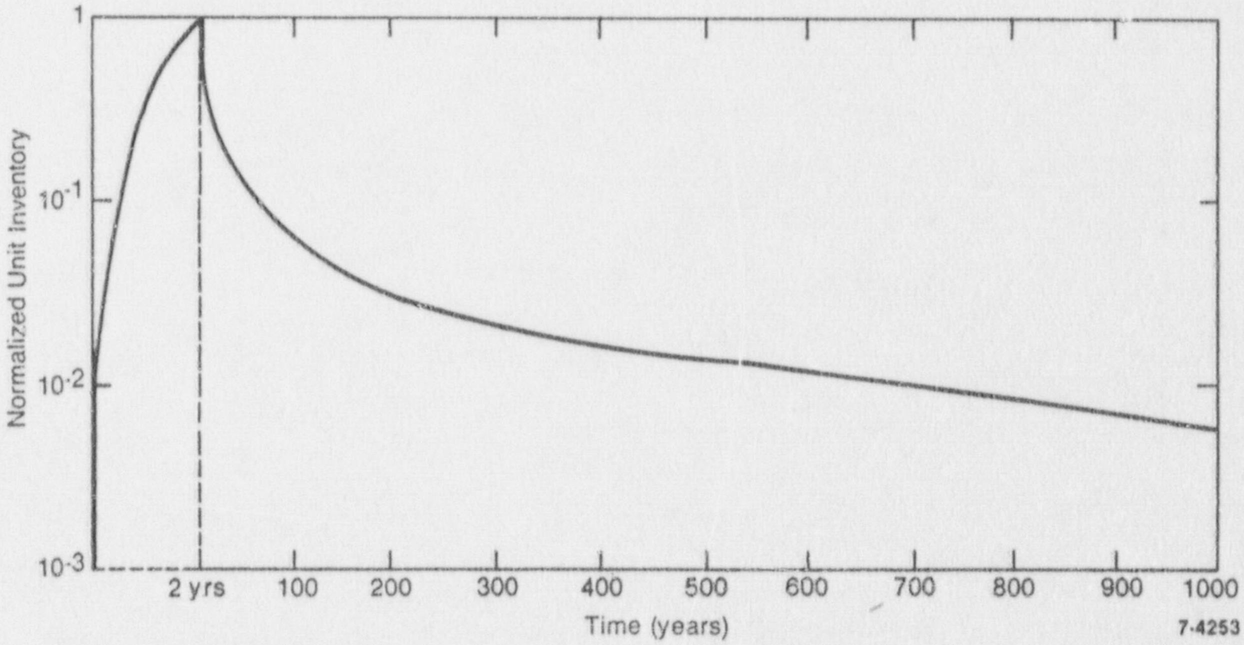

Figure 8. Normalized disposal unit radionuclide inventory.

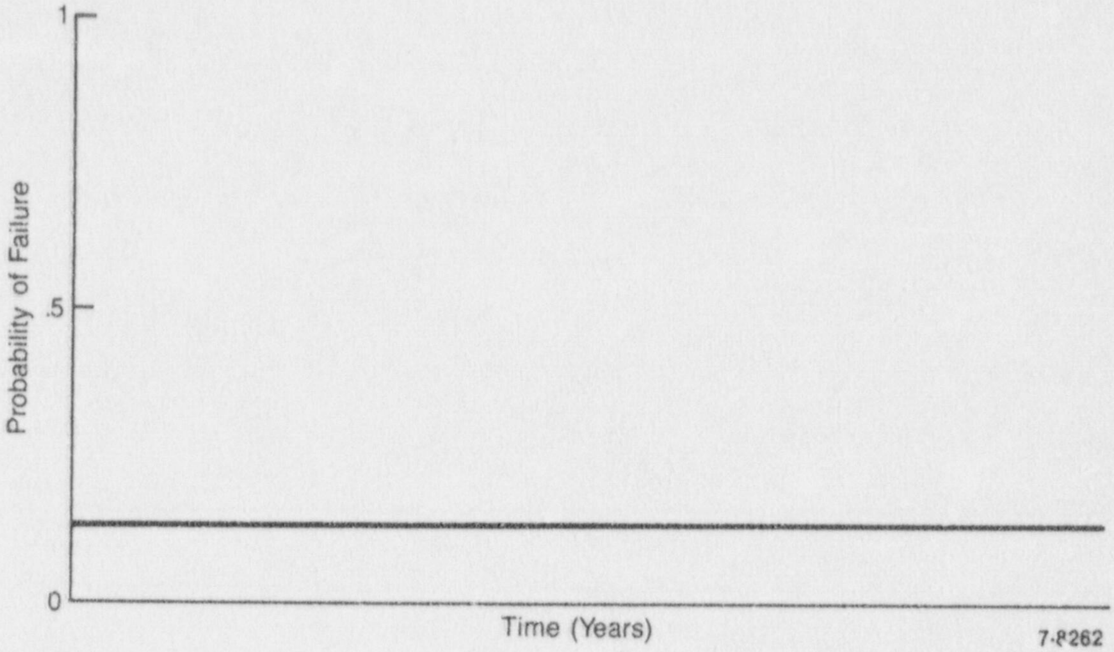

Figure 9. Generalized probability-of-failure curve for discrete event mechanism.

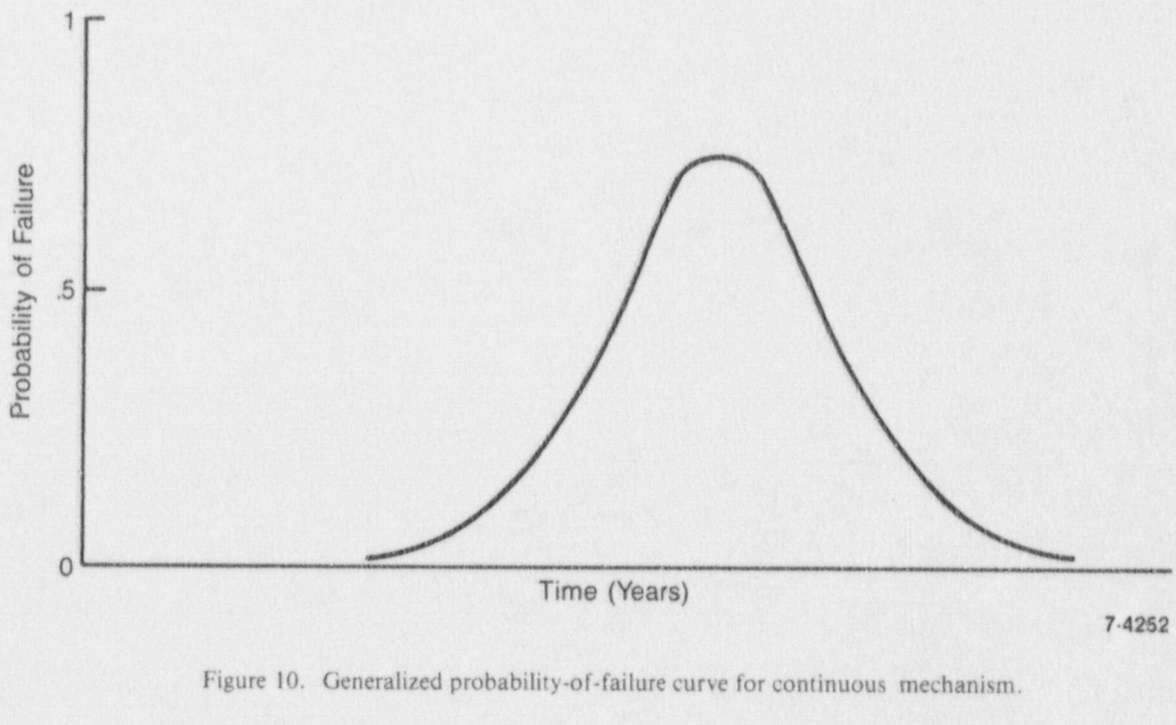

Figure 10. Generalized probability-of-failure curve for continuous mechanism.

The timing of failures becomes critical in determining the risk associated with a mechanism. For continuous processes, if the failures occur late enough in the unit lifetime, minimal risk (acceptable risk) is encountered.

The facility design also comes into play here. For example, an uncovered vault in a northern location would have continuous exposure to freeze/thaw cycles. On the other hand, a covered vault would have a POF due to freeze/thaw cycling which reflects the fact that it is exposed to this degradation mechanism only during the waste emplacement period (Figure 11).

Relative Risk by Mechanism. In order to narrow the field of degradation mechanisms to those of most concern, several of these concepts must be examined on a design-specific basis. Specifically, estimates of the probability of failure, the time of maximum POF, and the time frame over which the mechanism is active have been developed. These are presented in Tables 6 through 8 for aboveground uncovered vaults, covered vaults, and the cover component of vaults. In addition, it is important to take into account the time dependence of the radionuclide inventory when evaluating potential failure mechanisms.

Although all mechanisms are potentially active for uncovered and covered vaults, that is not the case for covers. Because covers are assumed to be constructed of natural materials, the chemical attacks and special concerns of radiation and biodegradation are not active. Also, the time frames over which many of these mechanisms are active change dramatically from uncovered to covered vaults. An uncovered vault is essentially subject to all mechanisms for its entire life. A covered vault, on the other hand, is no longer subject to discrete events other than an earthquake, nor is it subject to the mechanisms of wind and water erosion, biointrusion, mechanical settling, or freeze/thaw cycling once the cover is in place. For covered vaults, only chemical attacks are potential active degradation mechanisms. The brunt of the attack from the other mechanisms would be born by the cover, as can be seen in Table 8. This relationship can be seen even more clearly in Table 9. Once the cover is in place, the effect of all potential degradation mechanisms is split between the cover and the disposal unit. Each therefore copes with a smaller

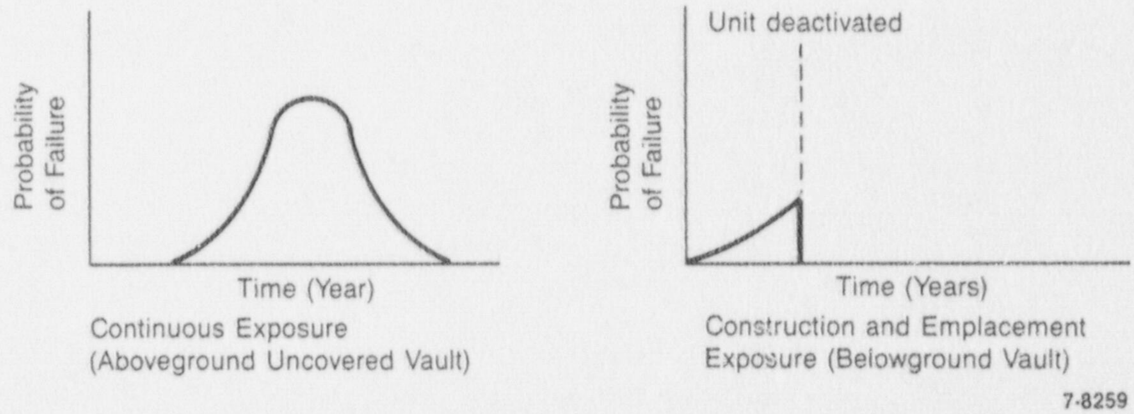

Figure 11. Probability of failure due to freeze/thaw for above- and belowground vaults.

Table 9. Potentially active degradation mechanisms for disposal options over the lifetime of the facility

Disposal Method	Degradation Mechanism														
	Fire	Flood	Storm	Earthquake	Wind	Water	Biological	Mechanical	Freeze-Thaw	SO_4	Acid	CL^-	$Ca(OH_2)$	Rad	Biodeg
AGV	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
BGV				X						X	X	X	X	X	X
AH				X						X	X	X	X	X	X
EMCB				X						X	X	X	X	X	X
Cover	X	X	X	X	X	X	X								

set of mechanisms. If concrete and cover material are properly chosen to ensure chemical compatibility, even potential chemical attacks on concrete can be mitigated by the presence of an earthen cover.

For all mechanisms and disposal technologies, the time of maximum POF is an estimate and is extremely uncertain. Such estimates were also necessary for the screening process, but data for the generic treatment of most potential failure mechanisms are sparse. Values presented in Tables 6 through 9 are sufficient to support a ranking of the relative risk associated with these mechanisms, but should not be used to predict the lifetime of actual engineered barriers. For the discrete mechanisms of flood, fire, wind storm, and earthquake, a linear-for-life estimate can be considered reasonable, based on the random nature of these events. Estimates for the continuous mechanisms are much less certain. This is reflected by the question marks listed in Tables 6 and 7 next to most chemical attacks. Only the sulphate attack estimate can be considered reliable because it is based on experimental data. In addition, this screening analysis does not include possible interactions among the failure mechanisms. For example, a fire that strips the vegetation cover off a disposal unit could cause the maximum POF due to water erosion to occur during the fire rather than after the end of the life cycle for the LLWDF. Therefore, the values provided for the mechanical degradation mechanisms should be considered as independent estimates only.

With these qualifications in mind, the rationales for the time of maximum POF estimates are as follows:

- For wind erosion, 200 years was chosen because of relatively high inventory and data available on soil erosion support treatment on this time scale.
- For water erosion, 500 years was chosen because it was assumed that water erosion would be controlled by several factors: slope, vegetation, and rip-rap. Should one be absent (vegetation, for example) the others would be able to control the water erosion rate to within design limits. Therefore, maximum POF due to water erosion was assumed to occur at LLWDF design life of 500 years.
- For biointrusion, 100 years was chosen. It was felt that, if burrowing animals or deep rooted plants were going to compromise the disposal unit, they would do it early in unit life. If none was seen at this point, chances of future intrusion as a result of these mechanisms was small.
- For mechanical settling, 2 years was chosen. If a problem with settling were to surface, it should occur shortly after construction or during the unit filling. Minimal settling was anticipated after these periods.
- For freeze/thaw cycling, 50 years was chosen. Given the observed deterioration rate of concretes already in place, 50 years may be optimistic. However, with proper air entrainment and other precautionary measures, concretes are purported to be immune to freeze/thaw effects. Therefore, 50 years was chosen since, if only minimal freeze/thaw effects are seen in this time frame, minimal effect would be expected for the remainder of the unit life.
- The 400 years for sulphate attack and radiation are based on recently published results.

The time frames were chosen to allow screening for highest hazard mechanisms and to illustrate an approach for a screening analysis. Once research provides more reliable estimates, revising of the list of important long-term degradation mechanisms will be appropriate.

Important Environmental Conditions

The analysis so far has assumed that these important environmental conditions contribute independently to each failure mechanism. This is a simplification that ignores both correlations in the occurrence of environmental conditions and interactions among failure mechanisms. Environmental conditions can be either positively or negatively correlated in occurrence. For example, the highly acid soils typical of eastern regions are associated with, and to some extent a result of, greater precipitation. Therefore, the occurrence of acid attack on concrete, and water erosion of covers, may be positively correlated. By the same argument, occurrence of acid attack and sulfate attack are negatively correlated. That is, it would be unlikely for both to be a problem at the same site.

Interactions between failure mechanisms are also possible. For example, spallation due to freeze/thaw cycling, and cracking due to mechanical settling, both provide sites for all forms of chemical degradation.

Data on correlations and interactions are more sparse than on the failure mechanisms themselves.

Consequently, it is possible to recognize the existence of such effects and identify some examples, but it is not possible to treat them quantitatively at this level of analysis.

Comparing Tables 6, 7, and 8 to the LLW unit inventory (see Figure 8), the following mechanisms emerge as those of greatest concern because of their continuous nature or because they are potentially active during the times when disposal unit inventory is high.

Uncovered Vault

Wind storm
Water erosion
Wind erosion
Biological degradation
Mechanical settling
Freeze/thaw cycling
Chemical degradation

Covered Vault/Augered Hole

Biological intrusion
Mechanical settling
Chemical degradation

Cover Component

Wind erosion
Water erosion
Biological intrusion
Mechanical settling

Combining the above lists yields the following degradation mechanisms as those of greatest concern:

Wind storm
Biological intrusion
Mechanical settling
Freeze/thaw cycling
Chemical degradations
Wind and water erosion

Several generalizations can be drawn from these lists. First, earthen covers can provide significant protection for structural concrete engineered barriers, particularly for wind and water erosion and freeze/thaw effects. In addition, chemical attacks on concrete result partially from incompatibilities between concrete materials and the surrounding soils. By providing appropriate soils in an earthern cover, these attacks on concrete components may be mitigated in the design of the disposal unit. This result is consistent with one of the major conclusions of our previous analysis. Uncovered vaults are more vulnerable to failure by all mechanisms than covered vaults independent of their relation to the original grade of the site.

Secondly, mechanical settling should be an important concern for all designs. Settling is most likely to occur during construction and emplacement when inventories and potential risks are high. Flaws due to settling can also provide sites for damage by other mechanisms, some of which may not be manifested until later in the life of the disposal unit.

Third, with the exception of severe storms during construction and implacement, discrete events do not appear to be high-risk failure mechanisms. This is true even when using 500-year recurrence intervals for severe floods and seismic events rather than more restrictive criteria. Annual probabilities are sufficiently low that occurrence during periods of high vulnerability and high inventory are unlikely. Occurrence during the longer period of institutional and passive control is more likely, but radioactive decay has significantly reduced potential risk during those time periods. In addition, site characterization data are often able to provide adequate estimates of recurrence intervals and intensities of such discrete events. Designing engineered barriers to withstand these events is also a relatively well understood process for which design criteria are available.[12,13]

Finally, chemical degradation of concrete engineered barriers is important for two reasons. It consistently ranks high in screening analyses, and data are not available to adequately determine rates of degradation on a site- and design-specific basis.

Potential Mechanism Interaction

The potential for some degradation mechanisms to promote others exists. For example, mechanical settling can cause cracking, which provides additional area over which chemical attacks can occur. These interactions can be qualitatively evaluated as in Figure 12. Where a plus sign appears in the figure, the mechanisms listed along the left-hand margin directly promote the mechanisms listed across the top. Only direct interactions are shown. An example of a direct mechanism is an earthquake's potential for generating mechanical settling. An example of an indirect interaction would be the enhanced potential for chemical attack in the cracks propagated during settling as a result of an earthquake. Such indirect interactions are not included in the figure.

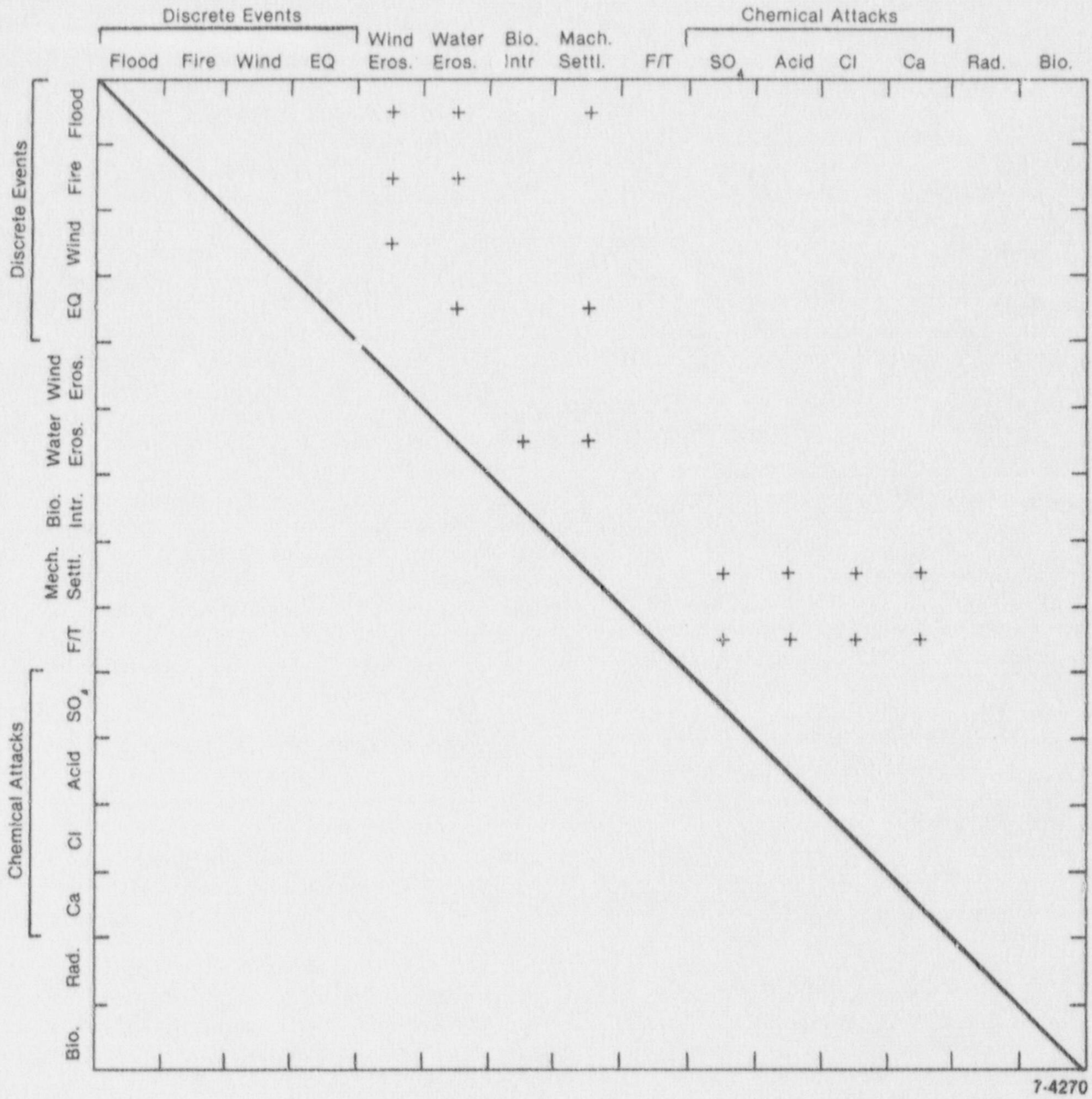

Figure 12. Potential direct mechanism interaction.

A number of generalizations can be drawn from an examination of mechanism interactions. Mechanical processes such as all of the discrete events and wind and water erosion can cause mechanical settling of both covers and structures and erosion of covers. Also, physical damage to concrete engineered barriers from settling and freeze/thaw cycling can enhance all forms of chemical attack by providing sites for action.

Beyond such qualitative generalizations, it is difficult to address interactions among degradation mechanisms. No data on the rates or extents of these potential interactions are available but potentially important interactions deserve further investigation. This is especially true with respect to chemical attacks and the interaction with mechanical processes.

Available Data on Structure and Cover Reliability

Cover Component Data. Many waste disposal industries other than LLW have a need for stable covers for various facilities. These include uranium mill tailings, sanitary landfills, and hazardous waste disposal sites. The prime reasons for installing a cover system are to minimize water infiltration, and to reduce the probability of human, animal, vegetative, or biotic intrusion.

The various sources on covers[14,15,16] have a common set of degradation mechanisms that are considered in cover design. These can be summarized follows:

- Cover consolidation/subsidence due to seismic events, cover settling, or covered material deterioration
- Freeze/thaw of moisture in the soil
- Water erosion
- Wind erosion
- Biological intrusion.

In the design of covers, a number of considerations are addressed, regardless of the cover's intended usage. These are to:

- Utilize naturally occurring materials to the maximum extent possible since they are least susceptible to degradation mechanisms (present fewer incompatibilities).
- Stabilize the material being covered and compact the cover material to industry standards. These precautions minimize the potential for differential settling and subsidence.
- Provide adequate material/vegetation to withstand expected wind/water/human/biological activities. The intent is to minimize water intrusion into the site and, as a result, reduce the potential for migration of materials from the site.

Data on cover design and performance appear to be adequate to address the needs of low-level radioactive waste disposal facilities. For alternatives to shallow-land burial which incorporate additional engineered barriers, particularly concrete structures, there may be specific considerations that require further investigation. In particular, chemical interactions between cover soils and concrete components deserve attention.

Structure Component Data. Because generic LLWDFs utilize concrete and/or steel as their main structural components, these materials were selected as the ones on which to concentrate data gathering efforts. New developments in high-integrity container design have led to the proposal of some fiber composite designs. These will not be addressed here.

Similarly, other materials that have only recently become available will not be addressed. These include epoxy coatings and other protectants for reinforcing steel, various sealants for concrete, and so forth. These materials have been in use for only a few decades at most, and their long term performance has not yet been demonstrated.

There are very few structural performance data available on either concrete or steel in the 100-to-500-year time frame and none at all on containment properties. Until recently, all applications have been structural in nature and have not addressed issues relating to radionuclide containment. In addition, analysis and modeling have been limited to a maximum 50-year time frame. Isolated examples of ancient cements, concrete building foundations and bridges in the 100-to-1000-year time frames are documented,[17] but incomplete information on the materials and their environments make application of the information to the current study difficult. As for current standards, models, and quality assurance criteria, they are aimed at the 50-year lifetime, and experts are uncertain of the reliability of the data or models if extended. One exception is Atkinson's[18] work on expected concrete longevity in sulfate environments. Using a combination of field coupons and models, estimates of structural lifetimes of 200 years (for ordinary Portland cement in a sulfate environment) to 700 years (for sulfate-resistant cement in a sulfate environment) to over 1000 years (in a benign environment) were derived. The latter two of these compare quite favorably with the LLW site 500-year requirements.

Steel also suffers from this same lack of data. The exceptions are very recent applications as high-integrity containers in radioactive waste containment. Existing corrosion models were refined and extended to the time frames of interest. Required material thicknesses were derived using these models and their calculated corrosion formulas.

Available data vary in both quality and quantity (from the single data point of a bridge, building foundation, or ancient structure to estimates of minimum, average, and maximum expected lifetimes). This range of data quality is graphically represented in Figure 13. The types of data and the probability of failure are presented in the upper graphs. The lower graphs present the integration of the probabilities over time (cumulative POF) and show when all units could be expected to be in a failed condition.

Because of the limited time over which LLW facility components have been under observation, no complete probability distribution data are available. The best available data are for the structural aspect of ordinary and sulfate-resistant concrete in sulfate environments and are from Atkinson (see Reference 18) and are shown in Figures 14 and 15. Figure 16 presents the expected lifetime data for steel high-integrity containers in all environments.

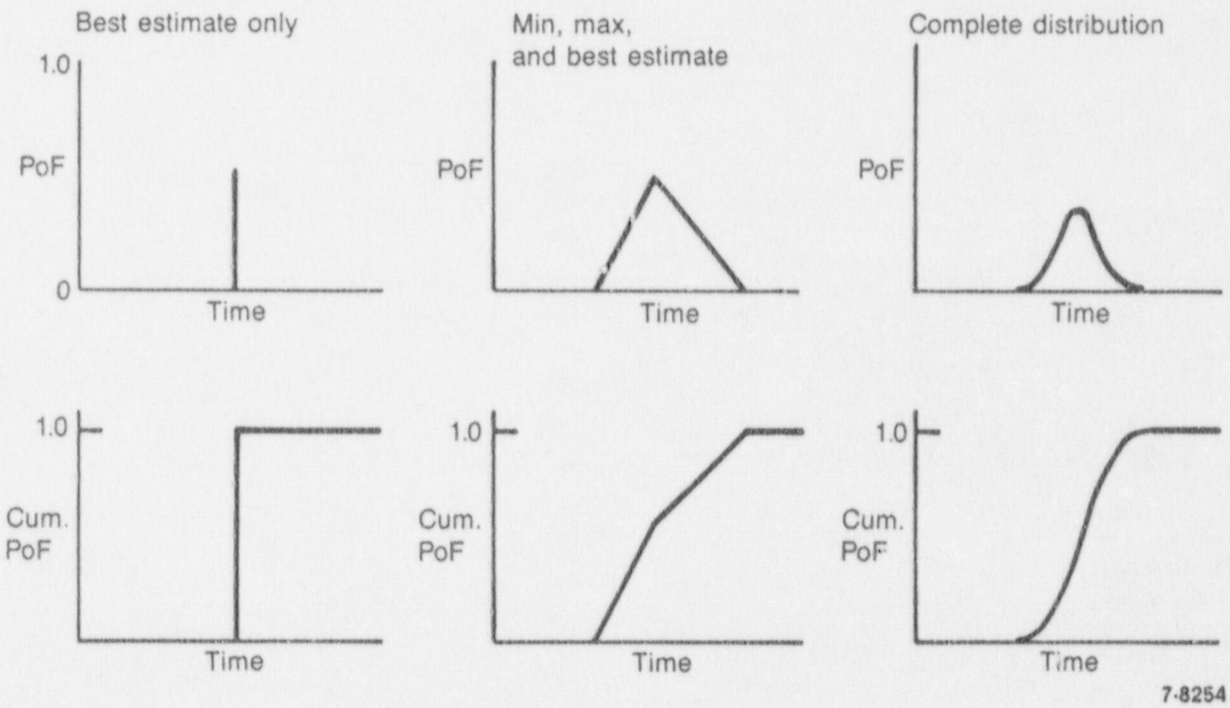

Figure 13. Probability-of-failure data quality variation.

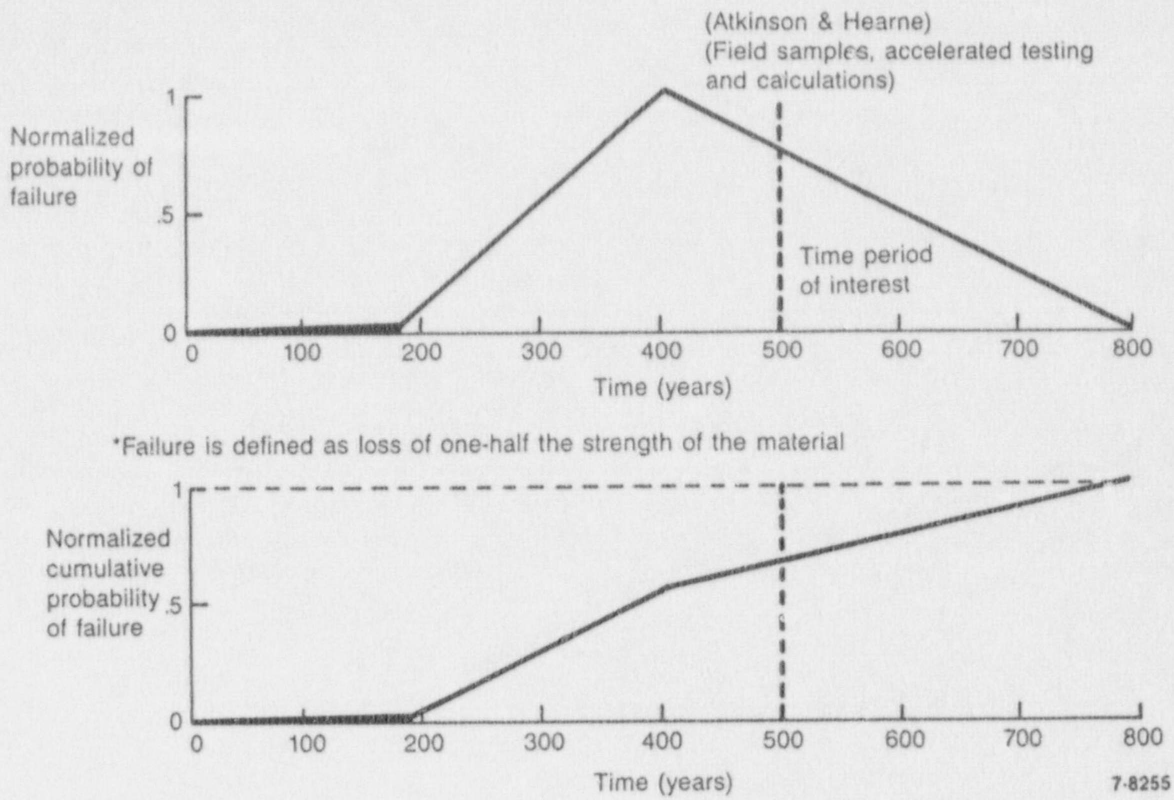

Figure 14. Probability and cumulative probability of failure for ordinary Portland cement in a sulfate environment.

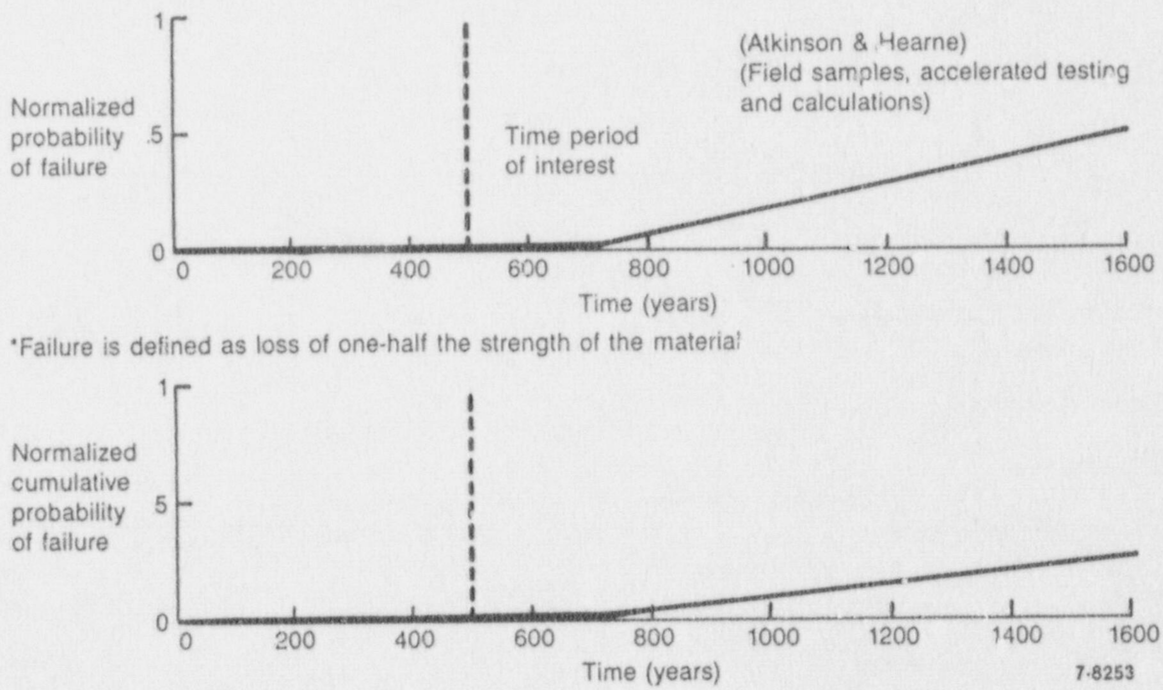

Figure 15. Probability and cumulative probability of structural failure for sulfate-resistant cement in a sulfate environment.

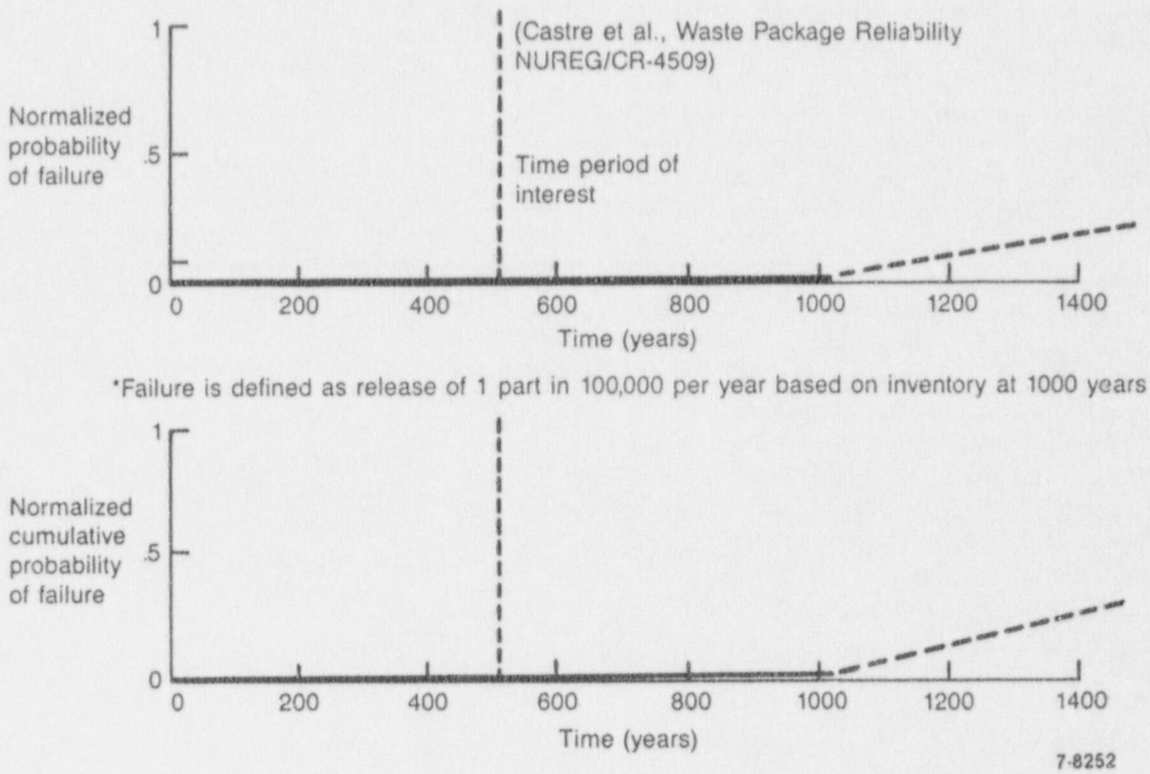

Figure 16. Probability and cumulative probability of failure for steel HICs.

CONCLUSIONS AND RECOMMENDATIONS

This report has described an approach for addressing the reliability of engineered barriers based on the results of previous work, which identified earthen covers and concrete structures as the most important categories of engineered barrier. The primary measure of reliability was assumed to be the performance lifetime or average time to failure of engineered barriers. A major emphasis was placed on the environmental conditions which promote failure by various mechanisms. The purpose of this document was to identify those environmental conditions which most limit the performance lifetime, and therefore the reliability, of engineered barriers.

One key to addressing reliability is a clear understanding of what is meant by failure. This analysis attempted to define failure in terms of physically measurable quantities that can be used as a basis for the development of engineered design specifications. It is important to note that, while the definitions of failure were based on the performance objectives of 10 CFR 61, they are to be applied to the engineered barriers, not to the disposal facility. Therefore, failure of individual barriers does not necessarily imply failure of the entire facility.

Two major categories of failure mechanisms were identified, each of which can be promoted by various environmental conditions. One category includes continuous processes, such as erosion of covers or chemical attacks on concrete. The other includes discrete events, such as floods and earthquakes. The fundamental differences between these two categories determine the nature of the data needed to estimate the mean time to failure as a consequence of each.

Engineered barriers need not, and cannot in principle, function forever. Fortunately, the hazard due to failure is closely associated with the toxicity of the waste inventory, which declines as time passes. This consideration allowed screening of both discrete events and continuous processes to determine which most limit the reliability of engineered barriers over the relevant time period.

The results of this screening analysis indicate that adequate data currently exist to allow designers to accommodate the degradation mechanisms of concern for covers.

- Cover consolidation/subsidence
- Freeze/thaw of the moisture in the soil
- Water erosion
- Wind erosion
- Biological intrusion.

Utilizing naturally occurring materials, properly compacted, and with adequate vegetation should result in a properly performing cover component for a LLWDF.

Mechanism interactions can be qualitatively identified. The strongest interactions are due to mechanical processes generating mechanical settling, and physical damage to concrete engineered barriers due to settling and freeze/thaw cycling enhancement of chemical attack potential. Further investigation is recommended.

Performance data on other engineered barriers, particularly concrete structures, either actual or modeled, are generally lacking for the time frame of interest. Two exceptions are for concrete in a sulfate environment and high-integrity steel containers used in high-level and hazardous waste disposal applications. Information on the behavior of these materials in the presence of the other environmental conditions does not extend to the 300- to 500-year time frame. The mechanisms for which data are needed are:

- Biological intrusion
- Mechanical settling
- Freeze/thaw cycling (aboveground vault)
- Chemical degradation (other than sulfate attack).

Some clear guidelines are available concerning the time periods over which data are needed. The desired performance lifetime should be in the time period of 200 to 300 years. The toxicity of low-level-waste inventories falls rapidly to very low values over this period and then remains essentially unchanged for a very long time. Designing for periods in excess of 300 years gains very little in terms of reduced hazard.

Having identified the most important failure mechanisms, further quantification of performance lifetime is hampered by limitations in the available data. There are three general observations that can indicate those areas needing further investigation. First, discrete events are generally better understood than continuous processes. Second, failure mechanisms (including continuous processes) are better understood for covers than for concrete structures. Third, failure of concrete is better understood with respect to structural strength than to radionuclide containment. Clearly, more information is needed on continuous degradation of concrete and on its containment properties.

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APPENDIX A

ACRONYMS ABBREVIATIONS AND GLOSSARY OF TERMS

APPENDIX A

ACRONYMS AND ABBREVIATIONS

AGV	Aboveground vault
AH	Augered hole shaft disposal
BGV	Belowground vault
CMFA	Common mode failure analysis
DOE	United States Department of Energy
EMCB	Earth mounded concrete bunker (tumuli)
FMEA	Failure mode and effects analysis
HIC	High-integrity container
ILTSF	Intermediate-Level Transuranic Storage Facility
INEL	Idaho National Engineering Laboratory
ISLB	Improved shallow-land burial
LANL	Los Alamos National Laboratory
LLW	Low-level waste
LLWDF	Low-level waste disposal facility
NRC	United States Nuclear Regulatory Commission
PRA	Probabilistic risk assessment
RF	Ranking factor
SLB	Shallow-land burial
TRU	Transuranic waste
TSA	Transuranic Storage Area
PO	Probability of occurrence
POF	Probability of failure

GLOSSARY OF TERMS

ACID ATTACK. Acidic water in contact with concrete attacks paste constituents.

AGREEMENT STATE. A state that has assumed regulatory authority under the Atomic Energy Act of 1954.

ALTERNATIVE DISPOSAL SYSTEM. A combination of engineered barriers that together form a disposal unit significantly different from that used in traditional shallow-land burial.

BIODEGRADATION. Metabolic attack on structural components by soil organisms.

BIOLOGICAL INTRUSION. Animal or vegetation intrusion into the cover.

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

CHLORIDE ATTACK. Seawater, brackish groundwater, or airborne salt compounds leaching paste components from concrete.

COMPONENT. A category of engineered barriers used in this analysis. The four components are cover, fill, structure, and container.

CONTAINER. A modular waste receptacle designed to provide greater structural stability and resistance to movement of water than a standard steel drum or wooden box.

COVER. An earthen cap containing design features to address 10 CFR 61 requirements for mitigating water infiltration, biotic intrusion, and erosion.

$Ca(OH)_2$ LEACHING. Removal of lime from cement paste by water.

DISPOSAL FACILITY FAILURE (STRUCTURAL). The disposal facility has failed if it has lost structural stability to such a degree that ongoing active maintenance is required or anticipated during and beyond the institutional control time frame.

DISPOSAL FACILITY FAILURE (CONTAINMENT). The disposal facility has failed if it no longer meets the 10 CFR 61 performance objectives of less than 24 mrem/yr (75 mrem/yr to the thyroid) for a member of the general public.

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

DISPOSAL UNIT. A discrete portion of the disposal site into which waste is placed for disposal. For traditional shallow-land burial, the unit is usually a trench.

DISPOSAL. The isolation of radioactive wastes from the biosphere inhabited by man and containing his food chains, by placement in a land disposal facility.

EARTHQUAKE. Seismic activity which generates rolling ground motion at the site.

ENGINEERED BARRIER FAILURE (STRUCTURAL). The engineered barrier (disposal unit) has failed if its structural component has lost 50% of its original strength.

ENGINEERED BARRIER FAILURE (CONTAINMENT). The engineered barrier has failed if it no longer provides resistance to the movement of radioactive material greater than that of the surrounding geologic medium alone.

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

FREEZE/THAW. Alternate freezing and thawing cycles which could result in stress-induced cracking or structural disruption of cement paste.

FILL. Any material placed in the interstices between waste to prevent collapse or subsidence, which may provide some structural stability and resistance to movement of water.

FIRE. Fire in waste due to lightning, vehicle spark, or fuel leak.

FLOOD. Overrunning of the site with water from an external source (such as a dam break or river excursion).

FUNCTION. A capability that an alternative disposal system must have in order to meet the performance objectives of 10 CFR 61 Subpart C.

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

INTRUDER BARRIER. 1. A sufficient depth of cover over the waste that inhibits contact with waste and helps to ensure that radiation exposures to an inadvertent intruder will meet the performance objectives set forth in 10 CFR 61. 2. Engineering structures that provide equivalent protection to the inadvertent intruder.

LAND DISPOSAL FACILITY. The land, buildings, and equipment that are intended to be used for the disposal of radioactive wastes into the surface of the land. For purposes of this report, a geologic repository as defined in 10 CFR 60 is not considered a land disposal facility.

MECHANICAL SETTLING. Dynamic differential settling due to addition of waste, barrier, and cover.

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

NORMALIZED TOXICITY. The sum of the number of curies of each nuclide weighted by their ingestion dose conversion factors.

RADIATION. Degradation (altering) of concrete paste constituents.

RISK. The probability of occurrence per year times the normalized radionuclide inventory at the time of failure.

STABILITY. Structural stability of the waste and disposal site so that, once placed and covered, access of water to the waste can be minimized.

STORM. Tornado or other severe wind storm.

STRUCTURE. A stabilized enclosure, sealed against the movement of water, providing resistance to subsidence or collapse.

SULFATE ATTACK. Waterborne soluble salt attack on cement paste constituents.

WATER EROSION. Removal of cover material due to normally occurring precipitation.

WIND EROSION. Removal of cover material due to normally occurring site winds.

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202 — U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1 REPORT NUMBER (Assigned by TIDC, add Vol. No., if any)

NUREG/CR-4701
Volume II

2 TITLE AND SUBTITLE

Safety Assessment of Alternatives to Shallow-Land Burial of Low-Level Radioactive Waste
Volume II: Environmental Conditions Affecting Reliability of Engineered Barriers

3 LEAVE BLANK

4 DATE REPORT COMPLETED

MONTH	YEAR
September	1987

5 AUTHOR(S)

Fred Cerven
Mark D. Otis

6 DATE REPORT ISSUED

MONTH	YEAR
September	1987

7 PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415

8 PROJECT/TASK/WORK UNIT NUMBER

9 FIN OR GRANT NUMBER

A6845-7

10 SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code)

U.S. Nuclear Regulatory Commission
Division of Radiation Programs and Earth Sciences
Office of Nuclear Regulatory Research
Washington, D.C. 20555

11a TYPE OF REPORT

Technical

b PERIOD COVERED (Inclusive dates)

12 SUPPLEMENTARY NOTES

13 ABSTRACT (200 words or less)

The need for new disposal capacity for low-level radioactive waste (LLW) has led to a re-examination of disposal practices. A number of enhancements and alternatives to traditional shallow-land burial have been proposed to meet the need for new capacity and to address various concerns about the performance history of existing commercial LLW sites.

This document builds on the results of the Volume I effort, which identified the important LLW disposal facility engineered barriers of cover and structure. Fifteen potentially important degradation mechanisms for a LLW facility are identified, categorized, and analyzed to determine their importance to the proper functioning of the disposal facility over its 500-year lifetime. Wind storms, biological intrusion, mechanical settling, freeze/thaw cycling, chemical degradation, wind erosion, and water erosion were considered the most important mechanisms. Data supporting concrete structure long-term performance in sulfate environments and long-term cover performance in erosive and biological intrusion environments were obtained. Research on the performance of covers and concrete structures in the presence of the other listed degradation mechanisms is recommended.

14 DOCUMENT ANALYSIS — a KEYWORDS/DESCRIPTORS

Shallow-Land Burial, Engineered Barriers, Belowground Vaults, Aboveground Vaults, EMCB Tumuli, Augered Holes, Degradation Mechanisms, Covers, Concrete Structures.

b IDENTIFIERS/OPEN-ENDED TERMS

15 AVAILABILITY STATEMENT

Unlimited

16 SECURITY CLASSIFICATION

(This page) Unclassified

(This report) Unclassified

17 NUMBER OF PAGES

18 PRICE

EG&G Idaho
P.O. Box 1625
Idaho Falls, Idaho
83415