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Low-Level Radioactive Waste Disposal Facility Closure

Part I: Long-Term Environmental Conditions Affecting Low-Level Waste Disposal Site Performance

Part II: Performance Monitoring to Support Regulatory Decisions

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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Part I of this report describes and evaluates potential impacts associated with changes in environmental conditions on a low–level radioactive waste disposal site over a long period of time.

Part II of this report contains guidance on the design and implementation of a performance monitoring program for low–level radioactive waste disposal facilities.

FIN No. A6853—Determination of Information Needed for Performance
Modeling of Low–Level Waste Disposal Facilities at Time of Closure

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PART I

LONG–TERM ENVIRONMENTAL CONDITIONS AFFECTING LOW–LEVEL WASTE DISPOSAL SITE PERFORMANCE

G. J. White
T. W. Ferns
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ABSTRACT

Part I of this report describes and evaluates potential impacts associated with changes in environmental conditions on a low–level radioactive waste disposal site over a long period of time. Ecological processes are discussed and baselines are established consistent with their potential for causing a significant impact to a low–level radioactive waste facility. A variety of factors that might disrupt or act on long–term predictions are evaluated including biological, chemical, and physical phenomena of both natural and anthropogenic origin. These factors are then applied to six existing, yet very different, low–level radioactive waste sites. A summary and recommendations for future site characterization and monitoring activities is given for application to potential and existing sites.

FIN No. A6853—Determination of Information Needed for Performance
Modeling of Low–Level Waste Disposal Facilities at Time of Closure

EXECUTIVE SUMMARY

The purpose of this document is to describe and evaluate the potential impacts associated with changes in environmental conditions on a low–level radioactive waste disposal site over the long term. For the purpose of this report, a timeframe of 100 to 500 years post–closure is used, which represents the time period between the end of the institutional control period (100 years) and the time at which the radionuclides contained in Class C wastes have decayed to acceptable levels with respect to public health and safety.

The performance of a low–level radioactive waste disposal facility is influenced by the hydrologic and ecological conditions found at the site. In turn, these conditions are strongly dependant on human land use patterns along with the climatic conditions found at the site. Any significant change or changes to these factors can potentially impact the ability of a waste disposal site to satisfy its performance objectives.

Factors that can contribute to these changes include chemical, physical, and biological processes, and can involve anthropogenic as well as natural processes. These complex and interacting processes can occur over wide spatial or temporal ranges.

Potential impacts associated with changes in those environmental conditions are illustrated with reference to six existing low–level waste disposal sites.

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PART I

LONG–TERM ENVIRONMENTAL CONDITIONS AFFECTING LOW–LEVEL WASTE DISPOSAL SITE PERFORMANCE

1. INTRODUCTION AND BACKGROUND

Site characterization activities performed during the licensing process, and characterization and monitoring activities conducted during operation, closure, and post–closure of low–level waste disposal facilities (LLWDFs), do not necessarily reflect the conditions that will be found 100 or 500 years into the future. Environmental conditions at a disposal site could deviate significantly from the expected conditions over the long term. The net result of such changes could be that a low–level radioactive waste disposal facility that meets licensing requirements in 1990 may not be licensable in 2090 or 2490, even if licensing requirements do not change during this timeframe. The purpose of this report is to identify and discuss how various factors, both natural and anthropogenic, may act to alter the conditions at a low–level radioactive waste disposal facility over the 100 to 500 year post–closure timeframe, such that the performance objectives of the site are no longer met. In effect, we are attempting to answer the question: "Are current licensing requirements adequate to ensure that the performance objectives of a licensed low–level radioactive waste disposal site are met in the long term?"

The 100 to 500 year timeframe is based on Federal regulations found in Chapter 10, Part 61 of the Code of Federal Regulations, "Licensing Requirements for Land Disposal of Radioactive Waste." During the required site characterization process, "site characteristics should be considered in terms of the indefinite future and evaluated for at least a 500 year timeframe" [10 CFR 61.7(a)(2)]. The 100 to 500 year timeframe represents the period between the end of the required 100 year post–closure institutional control period and the 500 year effective life of intruder barriers. This is related to the categorization of low–level waste (LLW) into Classes A, B, and C, as described in 10 CFR 61. Wastes categorized as Class A or Class B are required to contain only those types and quantities of radionuclides that will decay to non–hazardous levels during the 100 year timeframe. The 500 year period represents the time required for the longer–lived Class C wastes to decay to levels that do not "pose an unacceptable hazard to an intruder or public health and safety" [10 CFR 61.7(b)(5)]. The primary concern will therefore be associated with these long–lived Class C wastes.

Ecological processes discussed in this report are identified and evaluated in terms of their potential for causing a significant impact to a low–level radioactive waste disposal facility. In spite of the wide diversity of the processes identified in this report, many are interrelated. Categorization of the various processes is therefore very difficult. A number of potential schemes were evaluated for categorizing the processes in question. These methods were based on the following:

1. *The spatial range associated with the process*: Processes such as wildfire may impact only the immediate area of the waste disposal site. Other processes such as major deforestation may occur on a local scale of up to 10 km from the site. Processes such as widespread changes in agricultural practices might result in an impact on a regional scale of up to 100 or 1000 km from the site. Climate

change is a process that may occur on a global scale.

2. *The temporal range associated with the process*: Some of the processes identified, including wildfires, wind, and other storm events, occur over a short timeframe ranging from seconds to a few days. Other processes, such as impacts resulting from the widespread infestation of introduced forest pathogens or insect pests, may involve a timeframe ranging from a few days up to a few years. Processes such as changes in global climatic conditions or major changes in land use patterns, however, may require a much longer timeframe.

3. *Whether the process is anthropogenic or natural in origin*: Storm events, for example, are entirely natural processes, whereas mineral and energy production activities can be considered purely anthropogenic processes. Other processes may be associated with both natural as well as anthropogenic activities.

4. *Whether the process is chemical, physical or biological*: Chemical processes include the impacts associated with air pollution. Physical processes include the effects of wind and other storm events. The impacts associated with pathogens, insects, or introduced exotic species of plants and animals provide examples of biological processes.

5. *The means by which the process imparts its impact on the disposal site*: Some processes can cause a change in the hydrologic conditions at the site whereas others may impact the integrity of the cover system.

Ultimately, a combination of the methods listed above was used. This general approach described and categorized the various processes in terms of whether they would be expected to:

- Allow ground water to infiltrate the waste disposal unit from below

- Result in the loss of the integrity of the cover system so as to allow for either the release of waste to the above-ground environment or the entry of water into the waste disposal units from above.

Many of the processes identified in this report fall into both of the above categories. Furthermore, different processes would be expected to dominate at sites located in different geographical areas and climatic types.

Site performance is influenced most strongly by the hydrologic and ecological setting to which it is exposed. The local ecological and hydrologic conditions encountered at a given site are directly influenced by the climatic conditions and human land use activities. Land use is also strongly influenced by climate. The direct effects on site performance by climate and land use are secondary. These relationships are shown schematically in Figure 1.

Using Figure 1 as a conceptual basis, the processes discussed in this report were divided into three categories:

1. Processes that result from some change in land use pattern.

2. Processes that result from changes in climatic conditions.

3. Processes that exert direct impacts on plant or animal community structure, but cannot be attributed directly to human land use or climatic changes.

Recommendations regarding changes in licensing criteria to account for potential long–term changes in the site conditions of a low–level radioactive waste disposal site will be addressed in Section 5 of this report.

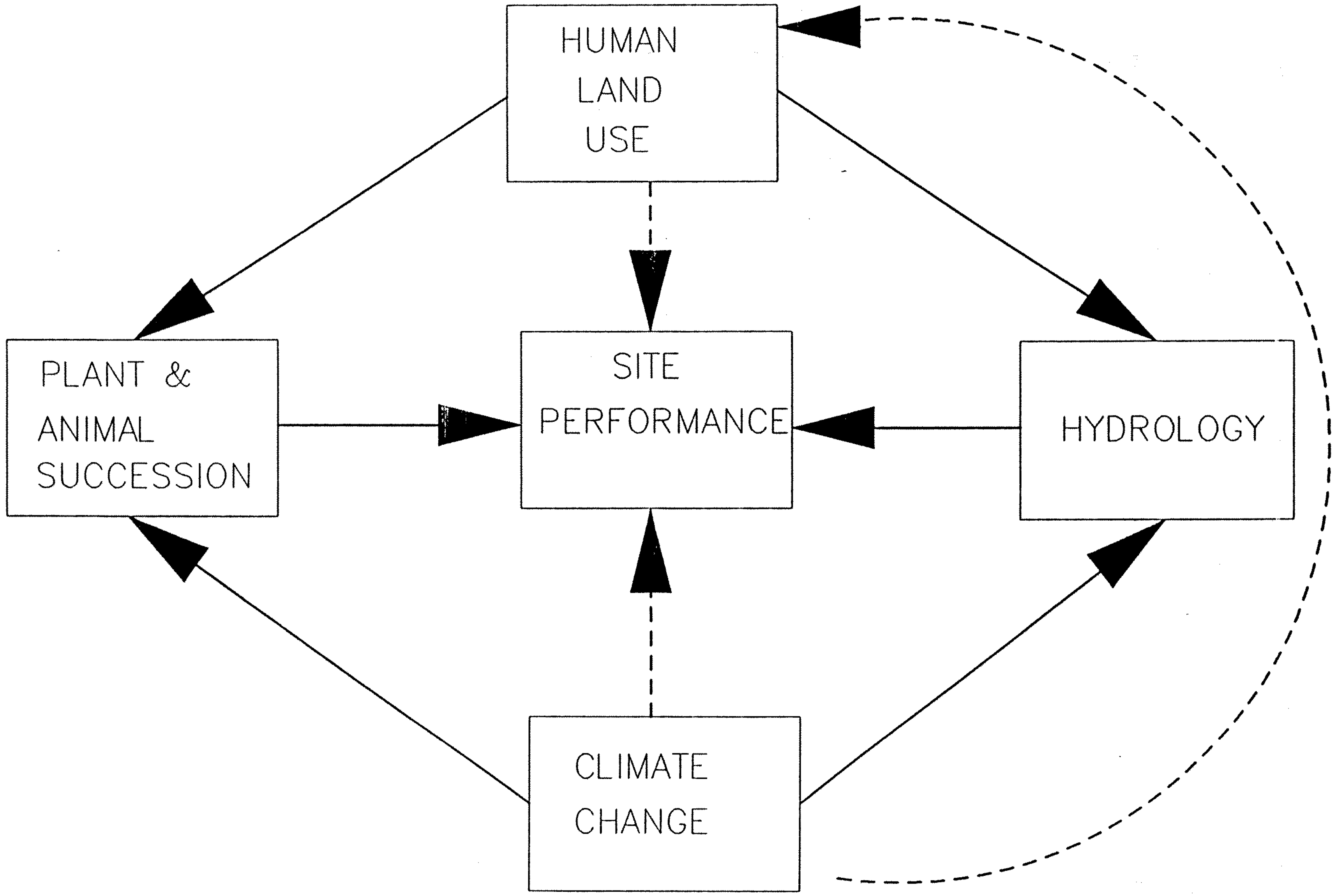

Figure 1. Interaction of environmental factors.

1.1 Summary of Pertinent Federal Regulations

Most of the Federal regulations that concern long–term environmental changes and their potential impacts at low–level radioactive waste disposal facilities are contained in Chapter 10, Part 61 of the Code of Federal Regulations (CFR): *Licensing Requirements for Land Disposal of Radioactive Waste.* Part 61 applies primarily to near–surface disposal facilities, although provisions are made for the implementation of additional regulations for alternative disposal technologies, should such technologies become available. Several such technologies have been described by others (Kane and Tokar, 1987).

Performance objectives for the disposal of low–level radioactive waste in near–surface disposal facilities are established in Subpart C of Part 61, and include the following:

- Protection of the general population from the release of radioactivity
- Protection of individuals from inadvertent intrusion
- Protection of individuals during operations
- Assurance of site stability following closure.

With respect to the impacts of long–term environmental changes on low–level radioactive waste disposal sites, it is clear that the fourth objective (assurance of site stability following closure) is of primary importance. In the long term (100 to 500 years), protection of the general population from releases of radioactivity will be accomplished primarily through ensuring the stability of the site. As stated in the regulations, the key to meeting the performance objectives is the stability of the waste disposal system. Once the waste is emplaced, the potential for water coming in contact with the waste must be minimized. By maintaining the stability of the site following closure, long–term active maintenance of the site can be avoided, potential exposures to intruders can be reduced, and migration of radionuclides can be minimized, [10 CFR 61.7 (b)(2)].

The 100 to 500 year timeframe used in this study represents the time period between the end of the 100 year institutional control period required by 10 CFR 61.7 (b)(4) and the 500 year effective life of intruder barriers required for disposal of Class C wastes by 10 CFR 61.7 (b)(5). Because Class A and Class B wastes are required to contain only types and/or quantities of radionuclides that will decay to non–hazardous levels in the 100 year timeframe, the primary concern is with the longer–lived radionuclides of Class C wastes. The maximum acceptable concentrations of various radionuclides in Class C wastes are specified in 10 CFR 61 such that the activities of each radionuclide will be at an acceptable level by the end of the 500 year period.

A major part of the licensing process as required by 10 CFR 61 is the submission by the applicant of site–specific technical information needed to demonstrate that the performance objectives and technical requirements can be met. Among the types of technical information required are detailed descriptions of a variety of environmental features of the site (10 CFR 61.12). These include:

- Meteorologic, climatologic, and biotic features of the disposal site and vicinity
- Design features related to infiltration of water; integrity of covers for disposal units; structural stability of backfill, wastes, and covers; contact of wastes with standing water; and disposal site drainage
- Design basis natural events or phenomena and their relationship to the principal design criteria
- Known natural resources at the disposal site (the exploitation of which

could result in inadvertent intrusion into the wastes after active institutional controls are removed).

A number of analyses are also required, including:

- Pathway analyses to demonstrate protection of the general population from releases of radionuclides. Pathways to be analyzed include air, soil, ground water, surface water, plant uptake, and exhumation by the activities of burrowing animals.
- Analyses of long–term stability of the site and the associated need for ongoing active maintenance after closure. This must be based on analyses of active natural processes such as erosion, mass wasting, slope failure, settlement of wastes and backfill, infiltration through covers over disposal areas and adjacent soils, and surface drainage of the disposal site. The purpose of these analyses is to provide reasonable assurance that there will not be a need for ongoing active maintenance of the disposal site following institutional closure.

When the detailed descriptions and analyses listed above are prepared during the licensing process, they are performed so as to reflect conditions currently encountered at the site and/or those known to have occurred at the site at some time in the historic past. Furthermore, post–closure surveillance required by 10 CFR 61 are to be based on the operational history and the closure and stabilization of the disposal site. Conditions present prior to and during the operational phase of the site, however, do not necessarily reflect conditions at the site 100 or 500 years in the future. Meteorologic, climatologic, and biotic features may be significantly different in the 100 to 500 year timeframe. For example, historic natural events and phenomena may not adequately reflect events in the centuries ahead. Natural resources not considered exploitable at the present may in fact become exploitable in the future as needs and technologies change. Natural resources exploited by future generations may not be recognized as such at the present time. Long–term changes in site characteristics may significantly alter the pathway and site suitability analyses required in 10 CFR 61. The net result of such changes could be that a low–level radioactive waste disposal site that meets licensing requirements in 1990 may not be licensable in 2090 or 2490, even if licensing requirements do not change. The purpose of this report is to identify and discuss how various factors may act to alter the environmental conditions at a low–level radioactive waste disposal site over the 100 to 500 year timeframe such that the performance objectives of the site may not be met. In effect, we will be attempting to answer the question: "Are current 10 CFR 61 requirements adequate to ensure that the performance objectives of a licensed low–level radioactive waste disposal site will be met in the long term?"

1.2 Document Organization

Section 2 of this document describes the establishment of baseline conditions at a given site. "Normal" or expected plant and animal community structure, hydrologic conditions, and climate are discussed, along with summaries of how unanticipated changes in these general factors might influence the ability of a low–level radioactive waste disposal site to meet its performance objectives. The assumption can be made that the set of baseline conditions established for a given site represent conditions found currently at the site in addition to those found in the historical past. It is this information that provides the basis for most site characterization.

Individual factors identified as potential contributors to the degradation of a facility are described in Section 3. Each factor is summarized briefly in terms of how it might operate to impact the hydrologic conditions or the plant and animal community structure of the site.

In Section 4, the processes described in Section 3 are applied to the six existing commercial low–level radioactive waste disposal sites. These sites are West Valley, New York; Barnwell, South Carolina; Maxey Flats, Kentucky; Sheffield, Illinois; Hanford, Washington, and Beatty, Nevada, and represent a wide variety of hydrologic and ecological conditions. The purpose of this section is to illustrate how different factors may be of concern in different geographic areas.

Finally, Section 5 provides summary of recommendations regarding how the regulations of 10 CFR 61 could be revised to better address the potential for long–term environmental impacts on LLWDFs.

2. ESTABLISHMENT OF ECOLOGICAL BASELINES

Site characterization during the licensing process is typically conducted using available data that is largely site–specific. Current conditions are characterized in terms of plant and animal community structure, hydrology, and climate, among other factors. Known historical variations in these factors are also typically provided. The assumption is usually implied (if not stated outright) that future conditions at a given site will not deviate significantly from those that have existed during the recent past. The validity of such an assumption is questionable, however, when the timeframe of interest is expanded to 500 years, if only because this timeframe exceeds the period of written history for most regions of the United States by at least a factor of two. The data collected during the characterization of the site can therefore be considered to represent the baseline conditions for that site. Future possible conditions at the site can be extrapolated and compared against this baseline information in order to determine how the overall system may change.

The purpose of this section is to describe how community structure, hydrology, and climate may vary under "normal" or baseline conditions, and to describe how subtle changes in these features may result in an impact on a low–level radioactive waste disposal site.

2.1 Changes in Plant Community Structure

Ecological systems are dynamic. As such, even subtle changes in any of a tremendously wide range of natural or anthropogenic variables can provide the impetus for significant changes in the structure and function of the ecosystem of interest. Because the original siting of a facility as well as the environmental monitoring program were based in part on an ecological characterization of a site, any significant change in the ecological characteristics of a site following the characterization could have a profound effect on the ability of a low–level radioactive waste disposal facility to achieve the performance objectives.

The purpose of this section is to briefly discuss the processes by which community structure, in the absence of disruptive factors, would be expected to change over the 500 year timeframe. The various factors that could act on the system over the long term resulting in a significant alteration in the structure and function of the ecological community, and how such changes could impact the performance of a low–level radioactive waste burial site after the institutional control period, will be discussed in Section 3.

Temporal changes in community structure are primarily of two types (Krebs, 1985):

1. *Successional changes*: directional changes in the structure of the community over time.
2. *Cyclic changes:* nondirectional changes in the structure of the community over time.

2.1.1 Successional Changes in Community Structure. When vegetation is removed from a site, the disturbed area will ultimately revegetate and return to its original condition, provided that the processes responsible for removal of the vegetation are no longer in operation. A variety of natural and anthropogenic factors can cause an area to lose its vegetation, including fires, floods, avalanches, glaciation, changes in agricultural or forestry practices, or development of facilities such as waste disposal sites, surface mines, or power plants. When left alone, however, most disturbed areas of bare ground will not remain devoid of plant and animal life. A variety of plant and animal species will eventually colonize the disturbed area. The introduction of each sereal stage results in subtle modifications of one or more environmental factor, such as air and soil temperature, shade, soil water, etc. In most systems, these changes occur rapidly, although exceptions such as desert systems, are recognized where the changes may not appear until the occurrence of some critical cyclic event such as an extended period of abnormal precipitation. Such minor environmental modifications in turn allow additional plant and animal species to become established. The process by which the action of organisms upon their environment results in the development of a community of new species is termed succession.

According to the classical theory of succession, species replace one another because the species present at the site at each successional stage (sere), make subtle modifications to the environment, so as to make the site less suitable for themselves and more suitable for other, more adaptive species. According to this theory, the replacement of species is therefore orderly and predictable, and provides the direction for succession. It should be pointed out that other theories of succession exist (Krebs, 1985), but for the purpose of this discussion we will concern ourselves only with the classical theory.

The first species to colonize a disturbed area are termed pioneer species. These species appear first in an area because they have evolved certain characteristics that enable them to readily colonize disturbed areas. This could include characteristics such as the production of copious numbers of seeds, high seed dispersal capabilities, rapid growth abilities, an annual growth habit, intolerance to shade, and a minimal dependance on mycorrhizal associates. Pioneer species are typically not well adapted to occupied sites where competition for space, water, sunlight, nutrients, or other factors exists. Community structure will progress, if left undisturbed, through a predictable series of successional steps until it reaches its ultimate or climax. This climax stage is the final or stable community in a successional series. The climax system is self–perpetuating and in equilibrium with its physical and biological environment.

In order to evaluate the effects of successional processes on a low–level radioactive waste disposal site over the 100 to 500 year timeframe, the following questions should be answered:

1. What are the expected stages in the ecological succession of the site following the period of active maintenance?

2. What reasonable alternatives exist to the expected pattern of succession?

3. Over what timeframe are the expected successional stages to progress?

4. What are the characteristics of the species comprising the successional sequence (both the expected and the reasonable alternatives) which could have an effect on the performance of the low–level waste site during the 100 to 500 year timeframe.

2.1.2 Cyclic Changes in Community Structure. Not all communities in equilibrium with their environments are static. A number of plant communities exist that undergo changes that are nonsuccessional and cyclic in nature. Cyclic events tend to occur on a small scale and are repeated over and over throughout the entire community. These events are part of the internal dynamics of the community rather than part of the successional process. A typical cycle could include a pioneer stage, a building stage, a mature stage, and a degenerative stage (Krebs, 1985). At the completion of the degenerative stage, the cycle begins again with the pioneer stage, and so forth. Several examples of cyclic changes in plant communities have been studied (Watt, 1947).

In order to evaluate the effects of cyclic processes on a low–level radioactive waste disposal site over the 100 to 500 year timeframe, the following questions should be answered:

1. What cyclic ecological processes are known to occur at the site (if any)?

2. At what stage of a cycle is the site during the characterization study?

3. At what stage of the cycle will the site be when active site maintenance is terminated?

4. What factors could occur to disrupt the cycle?

5. How would the structure of the community evolve once the cycle has been disrupted?

2.1.3 Natural Selection. As environmental conditions change, flora and fauna must adapt to the new environmental conditions if they are to survive. In order to survive as a species, organisms must change along with the environment. This can be a difficult task if conditions change faster than the organisms can adapt. Adaptation is conducted by means of interactions between the organisms and their environment. If an organism can tolerate a given set of environmental conditions such that it can not only survive, but can also leave an abundance of mature, reproducing progeny within the population, then the organism can contribute its genetic traits to the population gene pool. In this manner an organism can adapt to a changing environment. If the organism leaves few or no mature reproducing progeny, it does not contribute to the gene pool of the population, and is therefore poorly adapted to the environmental conditions. Those individuals that contribute the most to the gene pool of the population are said to be the most fit, while those that contribute little or nothing to the gene pool are the least fit. The fitness of an individual is measured by its reproducing offspring, and is therefore dependent on natural selection. The success of a species to adapt to a changing environment is not conveyed by the ability of an individual to survive, but rather by the ability to leave viable offspring. As conditions change, natural selection will act on the variation between individuals to alter the species such that it can survive in the new conditions.

Over a 500 year period, conditions in an area could conceivably change sufficiently that indigenous plants and animals would have to adapt in order to remain in the area. It is possible through the process of natural selection, for example, that a plant species may develop a deeper root system in response to a slow increase in temperature or decrease in moisture. Such a hypothetical change could have ramifications at a waste disposal site if the deeper root systems result in the failure of the disposal system to function adequately. Plant species identified in the initial ecological characterization of the site may have different characteristics 500 years later.

2.2 Effects of Biota on Waste Disposal Sites

The purpose of this section is to describe how flora and fauna might impact LLWDFs and to provide examples of such impacts.

2.2.1 Modes of Impact. Biotic intrusion may be defined as the actions of plants and animals that result in the transport of radioactive materials from low–level radioactive burial grounds to locations where radionuclides can enter pathways that could cause exposure to man. Burrowing animals result in the displacement of soil, and plant translocation of elements results in transport and redistribution of radionuclides in the waste trench cover and on the trench surface. The resulting soil concentrations of radionuclides may then contribute to the radiation dose to man through a number of exposure pathways including (a) direct exposure from contaminated surface soil, (b) inhalation of resuspended radioactive soil particles, and (c) ingestion of contaminated food products in the human food chain (Kennedy et al., 1985).

Three general methods or pathways by which biota act to transport radionuclides from waste disposal sites have been identified (McKenzie et al., 1982). These pathways include transport enhancement, intrusion/active transport, and secondary transport and are discussed below.

2.2.1.1 Transport Enhancement. Through this indirect pathway, biota enhances the transport of waste constituents by altering the physical environment surrounding the waste or by altering the waste itself. Transport enhancement occurs when waste constituents become more mobile either through the direct physical effects of the organisms involved, or more commonly in an indirect manner through some biochemical means. The end result is that potentially toxic constituents of the waste become more mobile within the environment. In effect, transport enhancement occurs when biota acts in a manner that modifies the immediate environment at the waste disposal site such that transport of waste constituents by other pathways is enhanced.

Examples of processes resulting in transport enhancement include the burrowing of animals that can affect the integrity of the cover even if the burrows do not reach the waste itself. The burrows created by the animals can allow rainwater to more readily enter the waste where they can solubilize and be transported in soil water. Burrows can also provide a pathway by which gaseous constituents or decay products of the waste may escape. The root systems of plants can also provide physical pathways with results similar to those of animal burrows. More recent work has indicated that organic ligands produced by plant roots and soil microbes can impact the solubility and mobility of radionuclides in the soil (Cataldo et al., 1987).

2.2.1.2 Intrusion/Active Transport. This represents a direct pathway by which waste constituents are translocated to the environment by the direct actions of plants or animals. In the case of plants, this process typically involves the uptake of radionuclides by roots and the subsequent translocation of these materials to the above–ground portions of the plant (Rickard and Klepper, 1976). Horizontal redistribution of materials within the root zone can also occur via the root system. In the case of animals, burrowing mammals and invertebrates can penetrate soil covers and mobilize contaminants from the buried wastes.

2.2.1.3 Secondary Transport. By this pathway, biota are considered secondary transport mechanisms in that they mobilize radionuclides from buried radioactive waste disposal sites only after they have first become mobile by some other means. For example, radionuclides may leach out of waste disposal units where they become available for further dispersal via the actions of biota. This can also involve the solubilization of radionuclides by organic ligands produced by plant roots and soil microbes (Cataldo et al., 1987).

2.2.2 Plants. Engineered barriers such as caps and liners are designed for relatively short–term operation (<100 years). Longer–term controls are also dependent on the environmental conditions present at the disposal site. The presence of any vegetative cover will serve to stabilize the site and reduce water infiltration. Surface vegetation covers are optimally selected to optimize these characteristics. After surface management practices are terminated, however, the plant species composition can be expected to change due to natural selection pressures, resulting in the disposal site eventually becoming dominated by one or more native climax species (Cataldo et al., 1987).

Vegetation, especially in the form of deep–rooted plants (phreatophytes), has long been recognized as a translocation pathway by which radionuclides can be released from radioactive waste disposal sites to the environment. Deep–rooted plants have been shown to be responsible for the translocation of radionuclides from buried wastes at several U.S. Department of Energy waste disposal sites, including the Idaho National Engineering Laboratory (LANL, 1977), Oak Ridge National Laboratory (Webster, 1979), Pacific Northwest Laboratory (Adam and Rogers, 1978; Fitzner, et al., 1979; Geiger, et al., 1977; Klepper, et al., 1979; Panesko, et al., 1980; USERDA, 1976), and the Savannah River Plant (Ashley and Zeigler, 1977; Cornam, 1979; DuPont, 1978; Horton and Corey, 1976). In these studies, the following radionuclides were observed to concentrate in plant tissues: H–3, Cs–137, Ce–144, Ru–106, Zr–95, Co–60, Pu–238, Pu–239, Pu–240, and Am–241. These studies indicate that radionuclides assimilated by plants and translocated above ground include fission products, activation products, and transuranic radionuclides, and that uptake occurs in both humid sites such as Oak Ridge National Laboratory and Savannah River Plant as well as in semi–arid sites such as the Pacific Northwest Laboratory, Los Alamos National Laboratory, and the Idaho National Engineering Laboratory. Plant species involved include grasses, shrubs, and forbs. Trees have also been found to be indicators of subterranean flow of tritium from the Maxey Flats commercial radioactive waste disposal site in Kentucky (Kalisz et al., 1988; Rickard and Kirby, 1987). Uptake of other radionuclides by trees has also been observed at Hanford (Landeen and Mitchell, 1986), at Savannah River (Pinder et al., 1984), and at Los Alamos (Hakonson et al., 1982).

A recent study has indicated that vegetation has the potential for modifying the chemical environment of the soil over the long term, thereby altering the mobility of radionuclides (Cataldo et al., 1987). Organic ligands produced by plant roots and soil microbes as part of the normal carbon cycle were shown in this study to alter the solubility and therefore the mobility of various radionuclides within the soil. The long–term implication here is that the introduction or invasion of plants onto low–level waste sites may increase the mobility of radionuclides in the soil due to the production of organic complexing ligands. Plant succession may change the rates at which growing and decaying plants produce these substances, thereby altering the soil chemistry.

The potential for radionuclide transport by trees and other deep–rooted plants at closed sites will increase after the active management of the site terminates. Over the 100 to 500 year timeframe, conditions at a site may change significantly in parameters that could have tremendous impact on the performance of the waste disposal site.

2.2.3 Animals. Burrowing animals, including both mammals and invertebrates, can potentially affect waste sites in a variety of manners. If allowed to burrow directly into the waste, animals can transport radioactive contamination in several manners (McKenzie, et al., 1982), including:

- Physically redistributing contaminants through activities such as digging and nest building
- Redistribution of external contamination received while in proximity of the waste during "normal" activities
- Ingesting contaminants and spreading contamination through waste products, carcasses, etc.

In terms of indirect effects, burrowing animals can enhance the transport of contaminants in several ways without burrowing directly into the waste area. Tunnel systems created by small burrowing mammals and invertebrates can increase the entry of surface water into the waste, allowing contact with the wastes and, ultimately, transport of contamination from the site. Preliminary field studies conducted at Pacific Northwest Laboratory indicate that high–intensity rainfall events can result in water entering the burrows of large mammals by three methods: (1) direct entry of incident rainfall, (2) runoff from microwatersheds created by soil cast to the surface by animals during excavation of the burrows (soil deposited near the burrow entrance acting as a dam to funnel water into the burrow), and (3) runoff flowing into the burrow from upslope (Cadwell et al., 1989). This study indicated that high–intensity simulated rainfall events penetrate to greater depths in burrow areas than in control locations. Many important characteristics of animal burrowing are not well understood even for those species studied. These characteristics include the number of burrows constructed per individual animal, the number of burrows constructed per unit area, the volume of soil displaced per burrow during construction, and the lifetime and fate of burrows once constructed. Before accurate predictive models of the impact of these animals can be generated, these and other characteristics must first be defined and quantified.

Burrowing activities have also been shown to result in the transport of waste constituents via increased erosion of the cover area (Winsor and Whicker, 1980). Gaseous waste constituents, including radon and organic compound decomposition products such as methane, tritiated water vapor, carbon dioxide, and hydrogen sulfide, are capable of escaping more readily from disposal sites whose cover system has been subject to the activities of burrowing animals. For example, prairie dogs (*Cynomys spp.*) are known to construct mounds in a manner that promotes wind–induced ventilation, which allows the venting of gaseous materials (Vogel et al., 1973).

Much of the evidence of burrowing animals on waste disposal sites has been derived from studies conducted at the Pacific Northwest Laboratory. Burrows of the Great Basin pocket mouse (*Perognathus parvus*) were found to reach depths of up to 1.4 m and involve volumes of up to 11,000 cm^3 of soil material per individual (Landeen and Mitchell, 1981). Contact with buried wastes by small mammals has been confirmed at Pacific Northwest Laboratory (Fitzner et al., 1979). Evidence of direct intrusion of larger mammals, such as badger (*Taxidea taxus*) or coyote (*Canis latrans*) has also been shown (O'Farrell and Gilbert, 1975). Mule deer (*Odocoileus hemionus columbianus*) have also been shown to redistribute radioactive contamination via secondary transport at Hanford (Eberhardt et al., 1984), as have coyotes at both Hanford (Springer, 1979) and the Idaho National Engineering Laboratory (Arthur and Markham, 1983).

At other sites, pocket gophers (*Thomomys talpoides*) have been shown to redistribute plutonium in soil in both the horizontal and vertical directions at Rocky Flats (Winsor and Whicker, 1980), while a similar species (*T. bottae*) has been found to disturb the cover of a low–level radioactive waste disposal site at Los Alamos (Hakonson et al., 1982). Small mammals have been shown to burrow into buried waste at the Idaho National Engineering Laboratory (Arthur and Markham, 1983), and radiocesium uptake has been found in cotton rats (*Sigmodon hispidus*) in the vicinity of waste sites at Oak Ridge National Laboratory (Garten, 1979).

With respect to invertebrates, several species of harvester ants (e.g., *Pogonomyrmex oweneei*) are known to tunnel to depths of up to 3 m and exhibit a preference for disturbed areas (McKenzie et al., 1982). Various researchers indicate that colonies of harvester ants may transport up to 150 kg of soil to the surface per year. Other insects that have been found to redistribute radionuclides from waste disposal sites and other nuclear facilities include honeybees (Eldridge et al., 1982) and various aquatic insects (Voshell et al., 1985). Earthworms, common in relatively moist sites, often possess elaborate burrow systems reaching depths of up to 2 m (Smith, 1974), and are capable of mixing large quantities of soil. Earthworms may be important factors in the secondary redistribution of waste constituents.

2.3 Seismic Conditions

Seismic events have the potential for changing the LLWDF siting assumptions considering the 500 year timeframe. The probability of a seismic event (earthquake) is always a serious design consideration for any constructed facility. Blasting from local construction or mining activity, accidents involving chemical, natural gas or gasoline tankers, etc. can mimic a seismic event.

On the large scale, seismic events can dramatically affect a LLWDF. Regional ground water tables and flow patterns can be affected by either changes in the regional tilt or the destruction of area aquifer systems. Areal erosional rates can be increased or decreased by shifts in stream erosional baselines. Rivers can be blocked creating temporary lakes (e.g., Quake Lake, Madison River, Montana) that might drastically affect the 100 year maximum probable flood (ympf) assumption. Mass wasting, subsidence, liquification, and other ancillary effects of an earthquake can have severe and immediate consequences for a LLWDF.

On the small scale, seismic events can also create real consequences for a LLWDR. Monitoring ports (e.g., aluminum neutron probe access tubes) can be cracked or snapped creating new pathways for infiltration/exfiltration. Even a minor seismic event (e.g., a sonic boom) could leave cracks in a clay cap or concrete barriers allowing water infiltration. It is the contributory effects (e.g., subsidence, liquefaction, elevational changes, and mass wasting) of a seismic event that are of interest to the LLWDF.

2.4 Hydrologic Conditions

The hydrologic system at a LLWDF is the most likely pathway for transport of radionuclides and other hazardous substances offsite (USDOE, 1983). Figure 2 shows the idealized hydrologic cycle. This section of the task has been designed to identify those ecology–related inputs that may affect the hydrology and therefore the performance of a site within the theoretical design timeframe of 100 to 500 years.

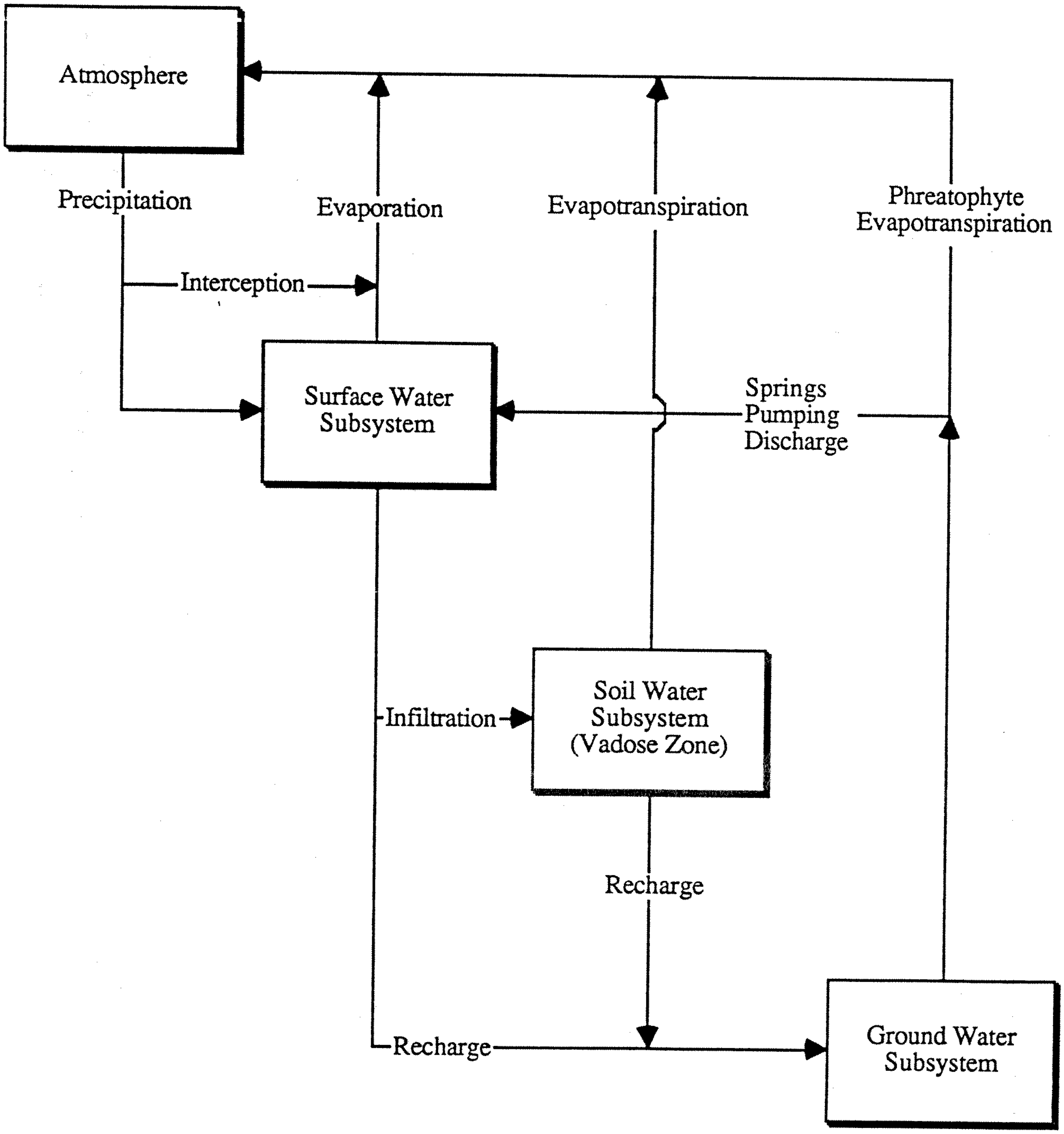

Figure 2. Linkages among the subsystems of the hydrologic cycle.

Flooding is perhaps the greatest natural catastrophic danger to a LLWDF. NRC's concern towards flooding is reflected in the siting criteria for flooding set at above the 100–year flood plain (10 CFR 61.50). Other geohydrologically–related environmental characteristics mentioned in the LLW disposal site suitability requirements are:

- Minimizing upstream drainage basin area
- No seepage from the geohydrologic unit within the LLWDF
- Low seismic activity
- No mass wasting (including slumping and landslides)
- Little erosion
- No enhanced weathering.

The geohydrologic system does not affect the aforementioned environmental processes in a direct cause and effect relationship. The effect of the geohydrologic system on the environmental processes, however, can be described in terms of a matrix. When a member of the matrix system is perturbed, the other parts of the system must adjust to compensate for the perturbation. For example, as previously discussed, an earthquake may produce a 10 ft scarp down drainage. The base level for that stream will then adjust to the new energy input (10 ft of gravity fall) at the scarp. Above the scarp, a process known as headwalling will begin and will increase the erosion rate in the area until a point of equilibrium between erosive forces and static forces is met. Headwalling erosion due to man's poor soil conservation practices downstream has been identified at the West Valley site. Below the scarp, there will be insufficient gravitational energy in the stream to carry the increased sediment load caused by the eroding headwall. The sediment in the stream will begin to fall out as the energy diminishes creating a fill ramp back towards the headwall area. In time, the scarp will erode away and the stream will return to a base level predicated on potential energy inputs from the atmosphere and the resistance offered by the local geology. This example shows how the hydrologic system adjusts to perturbations in a matrix manner.

The matrix is also evident in hydrologic changes induced by climate change. The hydrologic system should be examined as part of a global phenomenon. Factors that affect the climatic system will affect the local hydrology. Much concern has been recently expressed about the possible effect of global warming due to carbon dioxide buildup in the atmosphere from the burning of fossil fuel. The actual probability of global warming is addressed in Section 3. The real effect that would be expressed at a LLWDF would be a shifting in the climate pattern. Currently, the United States has two basic types of air masses: those areas where the ocean moderates temperatures and humidity (maritime), and those areas where the ocean does not moderate temperatures and humidity (continental). The interaction of maritime and continental air masses often determines the local climate. If the temperature of these air masses was to rise, then the interaction between the air masses would move northward. LLWDFs that were sited for a 100 year maximum possible flood (100 ympf) in an arid region might find that the 100 ympf is now 10 ft above the LLWDF and the site is now subject to a 50 ympf due to subtropical moisture moving northward. Similarly, a site that was located in a humid region may find that after extended drought, the precipitation interception zone attributable to vegetation is not the same. The retention time period and evapotranspiration factor characteristic of the unit hydrograph that was originally used to determine the 100 ympf is now inadequate. The 100 ympf elevation would now be higher due to the peculiarities of the runoff timeframe for a unit hydrograph in an arid environment. Figure 3 shows the shape of an efficient hydrograph (more erosive flash flood type of system) as opposed to a less efficient hydrograph (well vegetated with many retention periods). The added sediment load of the runoff from

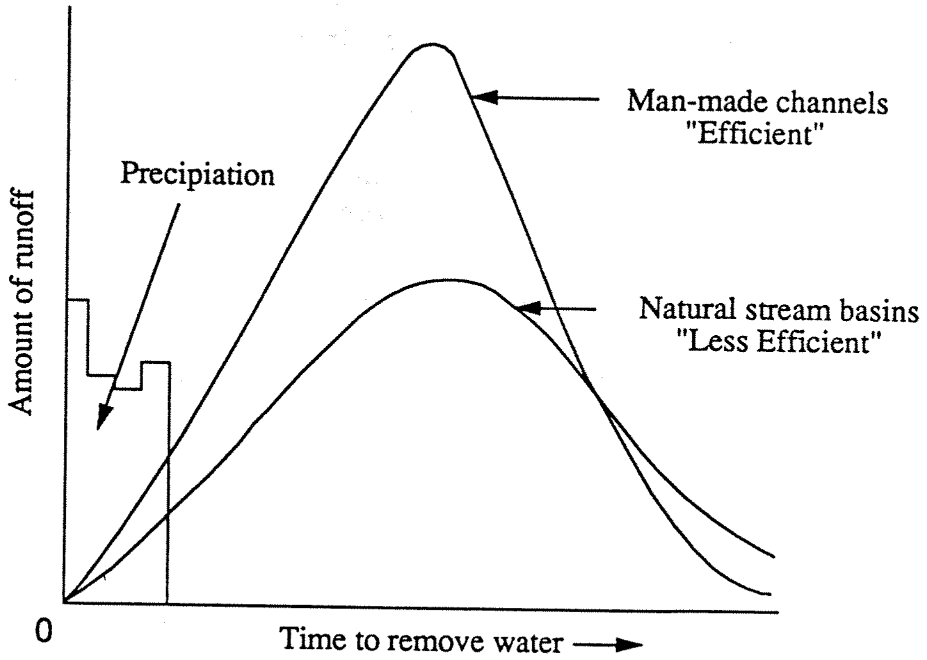

Figure 3. Idealized diagram illustrating the difference between an efficient drainage basin and a less efficient one.

erosion associated with an arid environment will exacerbate the problem by raising the elevation of the streambed. On the positive side, those LLWDFs sited in areas where a massive spring snow melt was of concern, would now lose the problem flash component of the unit hydrograph.

There are many elements to the geohydrology matrix set. Three broad categories can be used to organize the elements. These categories are:

- The atmospheric hydrologic system ending at the soil surface
- The infiltration into and the movement within the vadose zone
- The ground water movement controls.

The next three sections will discuss each of these categories in detail.

2.4.1 Atmospheric Inputs. The atmospheric hydrologic system is extremely difficult to predict in the short term and even more difficult in the long term. The major elements that control the atmospheric hydrologic system are the same elements that control the weather and, for the most part, the climate. These elements include: the intensity of solar radiation (a function of latitude), the reflectivity (albedo) of the earth's surface, the distribution of land and sea, and the local topography (Miller, 1976). The air mass is the vehicle for the expression of climatological elements. An air mass is a huge body of air extending over thousands of miles, which has a small internal gradient of temperature and humidity. Air masses are classified according to their source region, and masses can be either polar or tropical, as well as either maritime or continental. The most common types affecting the weather in the United States are continental polar, maritime polar, and maritime tropical air masses. Continental polar air masses originate in northern Canada. In winter, the air masses are stable and dry before moving southward to the United States where the warmer land mass heats the air from below causing instability. When these air masses move over a body of water such as the Great Lakes, water vapor is picked up and the leeward side of the lakes experience snowstorms known as "lake effect" storms. The lake effect is apparent at the LLWDF located in West Valley, New York). The maritime tropical air masses that affect the U.S. generally originate in the Gulf of Mexico. These air masses cause the spring rains in the southwestern deserts and the summer and fall hurricane seasons in the south central and eastern portions of the U.S. In winter, the maritime polar air masses from the Pacific are responsible for the winter rains experienced by the west coast. The Pacific maritime polar air masses leave more precipitation on the west side of the Rockies than the east because of the uplifting of clouds, or orographic effect. The rain shadow effect behind the prevalent wind direction of the orographic effect provides an excellent example of a micro–climate situation that makes broad based statements concerning climatic areas difficult.

Once the macro–hydrologic climate forces have provided precipitation, a secondary local hydrologic influence begins. The precipitation has several competing scenarios as to long–term placement. The route and speed of precipitation to its long–term storage location has important consequences to LLWDF performance predictions. Precipitation is likely to encounter either vegetation, organic litter, or impervious surface areas before it reaches a water body or the soil interface to the vadose zone. The different areas of moisture storage above the soil interface are varied and include: ponds, lakes, stream channels, leaves, stems, cryptogams, soil hardpans, rock depressions, pavement, rooftops, etc. If this moisture is in the form of snow, a probability for evaporation or sublimation exists, contingent upon relative humidity, ambient temperature, and wind speed; otherwise, the moisture is subject to evaporation, run off, or infiltration. The significance of the interception versus through–fall processes of precipitation at a LLWDF represent the lag effect of the ground cover and temperature on the unit hydrograph. Environmental changes that affect ground cover and temperature regimes also affect the hydrologic assumptions (unit hydrograph) by which the siting criteria were judged and on which the site performance objectives were based.

2.4.2 Vadose System. Once the moisture has reached the atmosphere/soil interface, the second category in the geohydrologic matrix begins. Vadose zone elements control the water/vapor movements once the conceptual infiltration line that separates the atmosphere from the soil is breached. The passing of the moisture from the atmospheric zone to the soil is termed infiltration. Factors that affect infiltration include:

- The existence of hydrophobic substances on the surface soil such as oily deposits found around creosote brush (*Larrea tridentata*) in the desert southwest
- Tillage practices that have promoted inwash of fine particles that block the macro–pores
- The organic content of the soil that facilitates infiltration by decreasing bulk density
- The non–montmorillonitic clay/montmorillonitic clay ratio that determines soil expansiveness
- The total amount of clay and organic colloids
- The bulk density of a soil that reflects the texture (percent sand, silt and clay) and compaction of a soil
- Raindrop size and previous moisture content of a soil.

Once the moisture has infiltrated the soil surface, the forces of the unsaturated zone are encountered, unless the soil is saturated to the surface. The unsaturated zone of an LLWDF is located in the upper part of regolith where water exists as vapor, or is mixed with pore spaces containing free air and free water (see Figure 4). The saturated zone (ground water or phreatic zone) lies beneath the vadose zone and non–existent in some arid sites. Perched water tables may exist above and/or below an unsaturated

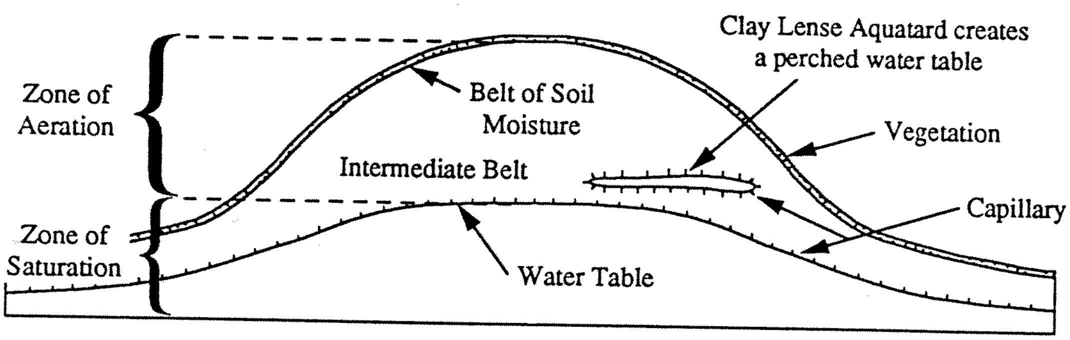

Figure 4. Idealized diagram showing the zones in which ground water occurs.

zone. A number of techniques have been developed for monitoring water chemistry and movement in the unsaturated zone (USEPA, 1983). Most of the monitoring techniques have been compiled and standardized in the American Society of Agronomy's book *Methods of Soil Analysis*, (edited by C. A. Black and published in 1986).

The vadose zone is the most complex of the three hydrologic zones (atmospheric, vadose, and phreatic) because the full spectrum of the physical and chemical atmospheric forces are combined with the full spectrum of water and geochemical forces found within the saturated zone. Within the soil/regolith matrix of the vadose zone there are two principal types of forces:

1. *The forces that produce a chemical gradient:* Examples include combinations of fluid properties (density, viscosity, dielectric potential, octanol/water coefficient or Kow, etc.) and solute properties [salinity (Eh), sodium adsorption ratio (SAR), acidity (pH), electrode potential (Eh), etc.].

2. *The forces that produce a physical gradient:* Examples include a complex mix of density, viscosity, particle size and distribution, porosity of the material, tortuosity of the pores, hydrostatic head pressures, barometric pressure differences, surface tension of different dielectric fluids, contact angle of the fluids with the pores, and local gravitational forces.

Trying to artificially separate chemical forces from physical forces reiterates the concept of the hydrologic matrix. For example, placing waste in a open trench or an engineered barrier sets up an electromotive potential based on the differences in oxidation states of reduced metals (steel drums) versus oxidized soils, or the pH state of concrete (12.5) vs. the pH of normal soils which is typically within a range of six to eight. Once the solvent (in most cases water) is added to the system, an electromotive circulation is set in motion much like that of a battery. The propensity for container degradation by a soil is best measured by the soils' redox potential. Eh–pH diagrams are used to determine the valance of an ionic species based on the Eh and pH of a particular soil. Eh–pH diagrams for iron, plutonium, strontium, and uranium are available in Dragun, 1988.

Waste is most likely to encounter moisture because of a natural tendency to transfer substances along gradients. Gradients are a result of the Second Law of Thermodynamics which states that, "in any spontaneous change the entropy (disorder) of the universe increases." Any system, such as a LLWDF, that tries to isolate a substance from the rest of the universe is fighting gradients and therefore the second law of thermodynamics. Water is the prime carrier of concern at the LLWDF, however radionuclides and other hazardous substances can move with other carriers. If there is free liquid (e.g., organics, mercury, etc.) buried with the waste or generated by microbial decomposition of waste, the free liquid can also transport the radionuclides. The relative humidity in a typically dry soil is 98%. The interplay (colloid chemistry) of the vapor, solid, and liquid phases of many compounds contributes to the probability of water being the ultimate transport carrier.

Carbon–14 (C–14) can exist in a solid matrix within the waste for example. Microbial degradation of the solid matrix could release the C–14 as carbon dioxide (aerobic) or methane (anaerobic) gases into the waste's voids. By the same process, water can also be internally formed. The C–14 will ultimately travel via the void spaces to the periphery of a LLWDF where it could come into contact with percolating water. The carbon dioxide gas would then react with the water to form carbonic acid resulting in the ultimate transport of the C–14 via ground water. The scenario for migration of tritium as either a gas or as a water molecule from a LLWDF is similar. This water envelope will always surround a LLWDF because water is an integral part of the environment.

Complicating the system even further is the fact that a given radionuclide can exist in several chemical forms, and each form can cause a significant difference in mobility in both the vadose and saturated zones. Chemically, the radionuclide can exist in several oxidation states, depending on the surrounding Eh and pH (Dragun, 1988). The oxidation state significantly affects the retention of the radionuclide on or in a clay matrix. The radionuclide can also exist as an organometalloid, especially when chelators such as amine polycarboxylic acids (e.g., EDTA, DTPA), hydroxy–carboxylic acids, and polycarboxylic acids (e.g., citric acid, carbolic acid, oxalic acid, and glucinic acid) are buried with the waste. Furthermore, the radionuclide can exist as an inorganic complex. Physically, the radionuclide can exist within the continuum of single element to a large elementally mixed colloids all of which have chemical behavior and thereby mobility implications.

2.4.3 Saturated Zone System. At the end of the vadose zone, or in perched water tables, exists an area known as the saturated (ground water) zone. Movement in the saturated zone has two components contributing to movement rates. The two components are hydraulic conductivity and total potential gradient. Hydraulic conductivity has several subcomponents that influence flow rates. Flow rates are affected by the fluid's properties such as density, viscosity, and dielectric constant. The physical flow system (i.e., if the flow follows pores, fracture, or a combination thereof) also controls the rate of ground water movement (see Figure 5). Pore properties include pore shape, size, distribution, and continuity. The continuity between pores can be influenced by several factors including particle size distribution, tortuosity, salt content, cation exchange capacity (CEC), colloid content, organic matter content, plant rooting, and burrowing animal activities. Where flow is through fracture zones, the parent material guides the type of fractures and thereby the resultant flow patterns and rates. The parent material can be massive (granites, basalts, limestones, etc.), layered (shale, sandstone, limestone, basalt flows, schist, gneiss, etc.), or unconsolidated (alluvial valley fills, slides, rockfalls, rotational slumps, recent pumice, sand dunes, etc.).

Besides fractures, there can be two other major influences on local ground water flow rates. Unconsolidated desert silts and clays containing a high salt content can be subject to a process, known as piping, whereby large underground conduits are formed. In limestone areas, karst topography can be the result of conduits dissolved through limestone. Giant sinkholes and underground rivers can be a consequence of water movement in limestone parent material.

In general, the pores and fractures control the flow direction and, to a major extent, the flow rate of a liquid (Tables 1 and 2). Fluid properties are also important. Organic chemicals having dielectric constants much different than water also can be a significant problem if the site assumes a transmissivity based on the dispersion of clays in water.

The total potential gradient causing movement around the LLWDF is generally characterized by three main components. These main components of potential gradient are pressure gradient, gravitational gradient, and chemical gradient.

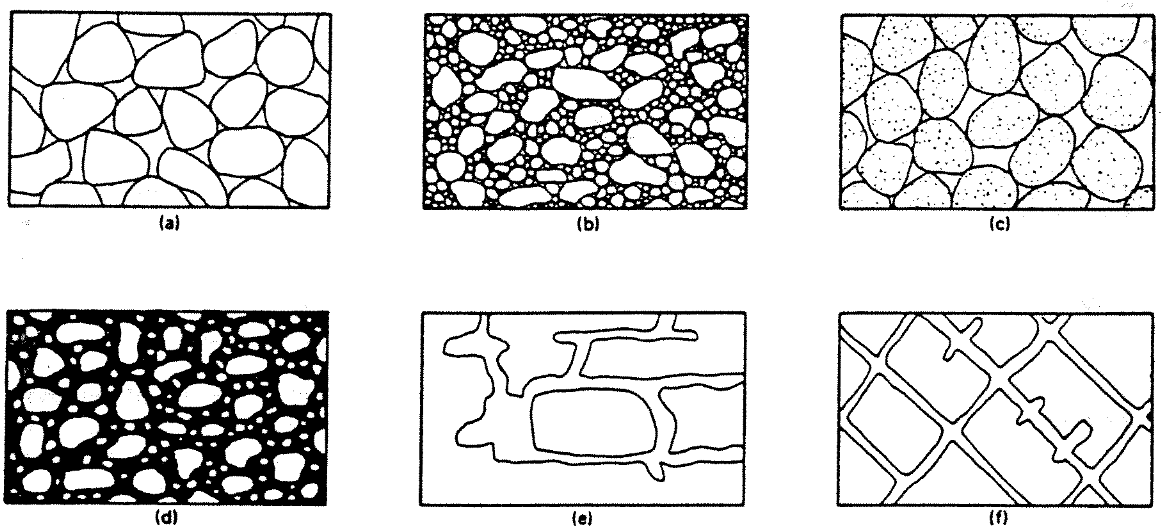

Figure 5. Idealized diagram showing several types of soil and rock openings and the relation to porosity.

Table 1. Some values of permeability for geologic materials (Dunne and Leopold, 1978)

Rock Type	Permeability (m/day)	Notes on the Most Common Control of Permeability
Clay	<0.01	Very small pores
Silt	0.0001–1	Small pores
Loess	0.0001–0.5	Depends on texture and amount of cement
Fine sands	0.01–10	Depends on texture (pore size)
Medium to coarse sands	10–3,000	Depends on texture
Dune sand	2–20 (average 8–10)	Depends on texture
Gravels	1,000–10,000	Large pores
Sand and gravel	0.3–10	Poorly sorted; fine grains plug large pores in gravel
Glacial outwash deposits	Up to 1	Often poorly sorted. Up to 10 m/day if very coarse or well sorted
Glacial till	0.001–10	Depends upon whether they are dense and silty ground tills, or sandy ablation tills
Sandstones and conglomerates	0.3–3	Size of intergranular pores, degree of cementation and of jointing

Table 1. (continued)

Rock Type	Permeability (m/day)	Notes on the Most Common Control of Permeability
Crystalline, unjointed limestones	0.00003–0.1	Very few pores; jointed limestones, however, can have very large and variable permeability
Gabbro	>0.0003	Few pores, permeability depends on degree of jointing
Granites and granodiorites	0.0003–0.003	Depends on degree of jointing, deeply weathered granitic rocks, however, can have permeabilities in the range of 0.003–3 m/day
Volcanic tuffs	0.003–3	Depends on depth of burial and compaction
Lavas	0.003–3	Depends largely on degree of fracturing, but weathered surfaces may be highly permeable

Table 2. Characteristics of aquifers (Dunne and Leopold, 1978)

Material	Thickness (m)	Transmissivity ($m^3/m/day$)	Storativity ($m^3/m^2/m$)
Unconsolidated Rocks			
Glaciofluvial deposits, Hanford, WA	9–14	4700–37,000	0.06–0.20
Alluvial sand and gravel Gallatin Valley, MT	8	1,240	0.006
Alluvial fan deposits Gallatin Valley, MT	19	450	0.06
Sand and gravel outwash Mattoon, IL	5	320	0.0015
Sand and gravel outwash Barry, IL	11	1,490	0.003
Valley train sand and gravel, Fairborn, OH	24	3,470	0.0008

Table 2. (continued)

Material	Thickness (m)	Transmissivity ($m^3/m/day$)	Storativity ($m^3/m^2/m$)
Glacial outwash Providence, RI	18	4,340	0.007
Young, gravelly alluvium Willamette Valley, OR	6	11,000–25,000	—
<u>Consolidated and Semi–Consolidated Clastic Rocks</u>			
Carrizo sandstone Lufkin, TX	37	400	0.000238
Aquia greensand Coastal Plain, MD	6	125–250	0.00023
Spilsby sandstone Lincolnshire, England	—	70	0.0002
Bunter sandstone South England	—	—	0.019
<u>Igneous and Metamorphic Rocks</u>			
Weathered wissahickon schist Baltimore Co., MD	20–30	40–125	0.001–.01
Snake River Basalts, ID	—	1240–223,000	0.02–0.06
<u>Carbonate Rocks</u>			
Fort payne chert (limestone) Madison CO., AL	6–110	60–17,000	0.00045–0.0289 0.005 (average)
Renault–St. Genevieve limestone Hopkinsville, KY	38–53	1560 (average)	0.00029 (average)
Tymochtee dolomite, Ada, OH	70	100 (average)	0.002 (average)
Silurian dolomite	75	750	0.00035
Chalk, SE England	—	<110–4,200	0.015

The pressure gradient is most commonly mentioned in context with semi–aquacluded (aquatard) or aquacluded aquifers. A confining layer of clay overlying an aquifer may preclude water from releasing at a gravitational gradient. The water pressure builds to greater than gravitational and atmospheric gradients and an artesian well is produced when the aquatard is breached (Figure 6). A pressure gradient is also evidenced by movements of atmospheric pressure centers. The level of water in a production well will increase when an atmospheric high leaves an area and is replaced by a low pressure system.

The gravitational gradient is somewhat variable (the force of gravity is a constant) depending on the density of the fluid. Certain organics that have molecular densities greater than water, such as trichloroethylene (TCE), have been termed "sinkers" because they tend to move more in a downward direction than the water flow they travel in. By the same reasoning, other organics that are lighter than water or hydrophobic, such as ethyl–alcohol or alkanes, respectively, are called "floaters" because they tend to accumulate on top of the saturated zone.

The chemical gradient is expressed by water traveling to areas of higher salt content because of the osmotic pressure differential. At a LLWDF, this essentially means that a waste form consisting of a desiccated salt (e.g., NO_3^-, Cl^-, or $SO_4^=$) will attract water due to the osmotic gradient and facilitate ion removal from the salt by the osmotic gradient.

Radionuclides migrate at different rates because of the aforementioned factors. The primary performance objective of a LLWDF is to limit the migration of the LLW so health based risk factors are not exceeded. Perturbations in the hydrologic cycle can change the assumptions that the original LLWDF was sited on and the performance objectives were designed to. The monitoring program at a LLWDF must account for changes in both LLWDF induced parameters and background parameters. Multi–factorial ANOVA is a reasonable statistical test used to separate natural trends from induced trends. Autocorrelation in space and time, however, should be accounted for.

2.5 Summary

It can be seen from these examples that the characteristics of plants, animals, seismic conditions, and the regional hydrology and geology can produce significant impacts on the performance of radioactive waste disposal sites. The processes that cause these impacts are variable, and may be either direct or indirect. Furthermore, these types of processes are not restricted to specific geographical regions of the country, but may occur in either wet or dry sites, provided local conditions are conducive. Biota has been shown to interact with abiotic factors such as erosion, leaching, and percolation of surface water to increase the mobilization of wastes.

The licensing requirements contained in 10 CFR 61 are intended to address these and other environmental problems such that the impacts of these processes are minimized either through the site–selection process or through the engineered design features of the disposal facility. Management programs at shallow land burial sites, which include active maintenance of the site such that deep–rooted plants and burrowing animals are excluded, appear to be effective in limiting or eliminating biotic transport of waste from the burial site in the short term. However, cessation of such maintenance activities following the post–closure maintenance period will provide no guarantee that biotic intrusion will not be an important factor in the longer, 100 to 500 year timeframe. Plants and animals that do not contribute to the degradation of the integrity of the site over the 100 year timeframe may impart significant damage during the 100 to 500 year timeframe. It is possible that the actual conditions at the waste disposal facility in the future could deviate significantly from what was expected after closure. It is therefore important to expand the range of concern so as to consider not only the expected, but the conceivable as well.

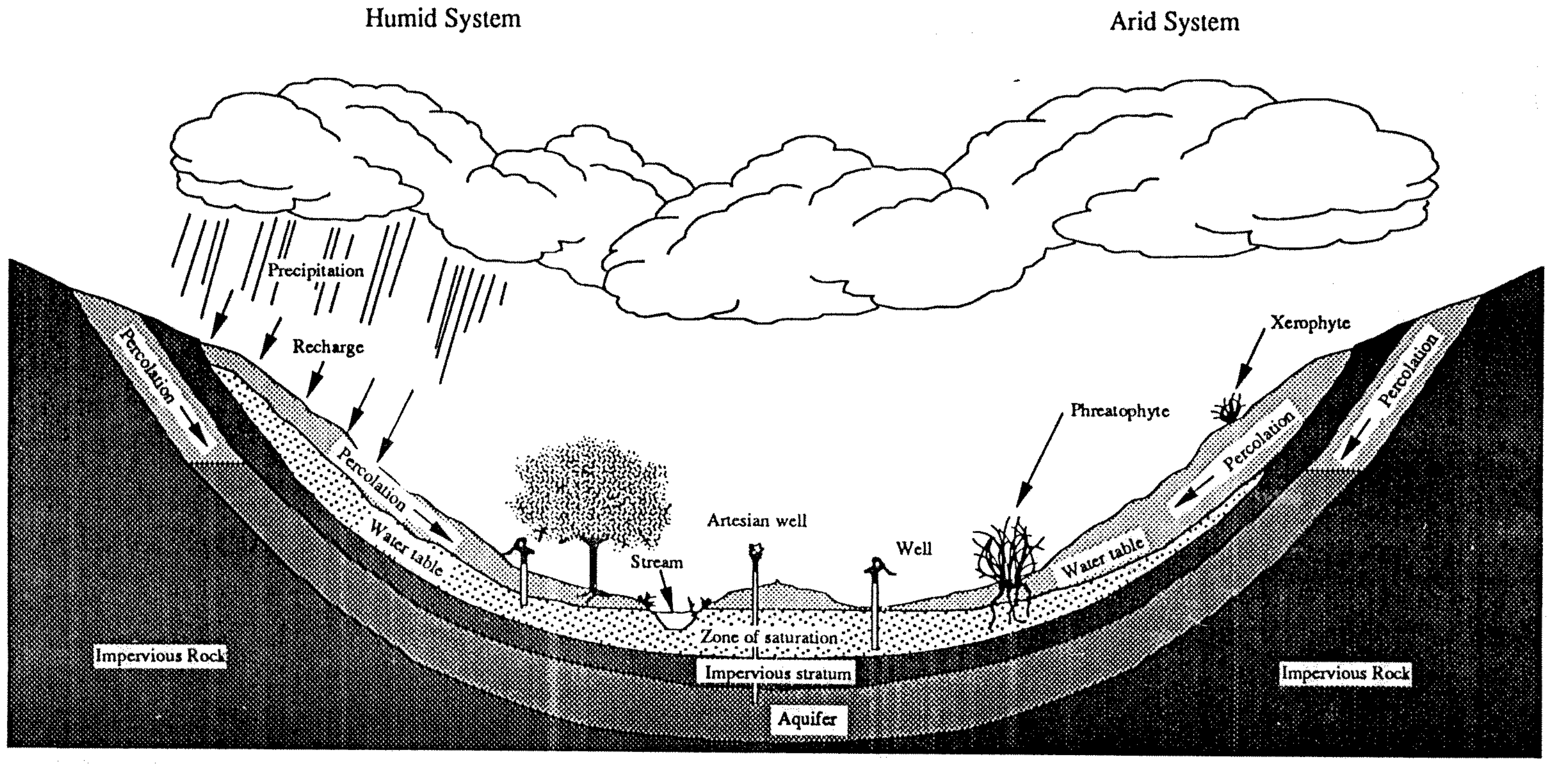

Figure 6. The ground water system.

3. FACTORS THAT MIGHT DISRUPT THE SYSTEM

3.1 Introduction

The previous sections described the significance of changes in plant community structure and hydrologic conditions at a waste disposal site under predictable and expected conditions. A number of factors could, however, act on the system causing a deviation from the predicted. The possibility of a deviation is especially relevant when considering the relatively long 100 to 500 year timeframe used in this study. The disruptive factors may include biological, chemical, and physical phenomena of both natural and anthropogenic origin, operating over time scales ranging from seconds to centuries or longer. The potential result of these phenomena is the existence of a community structure and/or hydrologic conditions that are significantly different from those originally predicted for the site. Figure 1 graphically illustrates the interrelations of hydrology, ecological succession, human land use, and climate change as they would ultimately affect the parameters upon which site performance is based. The implication to the long–term impacts on a low–level radioactive waste disposal site is that the environmental characterization used in the performance assessment and design criteria calculations under which the facility license was approved may no longer be applicable to the site. If, for example, certain factors operating over the 400 year timeframe following the period of active site maintenance result in the introduction of plant species with exceptionally deep root systems, or burrowing animals not previously known to exist at the site, measures originally designed to prevent biological intrusion into the site may no longer be adequate. Similarly, changes in meteorological conditions at a site could result in an increase outside the original design envelope in wind or water erosion at the site, or in a change in the depth of frost penetration. Direct changes due to anthropogenic activities can also have a tremendous effect on the site, particularly in terms of their impact on the water table, and may be the most difficult factors to predict.

It becomes apparent that in order to ensure that the site meets its performance objectives over the 100 to 500 year timeframe, the realm of biological, physical, and chemical factors examined cannot be limited to that which has been known to have occurred at the site during the historical past, but must also consider virtually every conceivable combination of factors that could occur at the site over the course of the next five centuries. A list of important disruptive factors is provided below.

3.2 Effects of Changes in Land Use

Changes in land use patterns can have significant impact on the performance of a LLWDF. As with the factors described above, changes in land use patterns can impact the hydrologic conditions or disrupt the plant community structure at the site.

The potential impacts resulting from changes in land use patterns would be expected to fall into one of three general categories:

1. Direct impact on the integrity of the waste disposal site and surrounding areas.
2. Indirect impact on the community structure of the waste site and surrounding areas.
3. Indirect impact on the hydrology underlying the area including the waste site.

It can be assumed that the site ownership requirements of 10 CFR 61 directed toward the prevention of inadvertent intrusion at the site, will eliminate the concern for the first category of impacts listed above. The more indirect effects associated with changes in land use patterns on plant community structure and ground water hydrology are similar to those described in previous sections. In general, impacts due to changes in land use patterns are of importance on a regional scale. Impacts on plant community structure and ground water hydrology due to long–term changes in land use patterns may not be adequately addressed in the current regulations.

Predictions of future conditions at a waste disposal site (or any other type of site) are often hindered due to an incomplete knowledge regarding future scenarios. This lack of prescience is more of a problem when considering anthropogenic activities as compared to natural factors.

Major categories of land use that can result in impacts to the surrounding plant community structure and/or ground water hydrology include agriculture, forestry practices, extraction of energy, water, and minerals, and urbanization. Each of these activities is described below.

3.2.1 Agriculture. The primary significance of agricultural practices to the long–term integrity of LLWDFs involves the potential impact of agricultural activities on local and regional hydrology. There are two primary mechanisms by which agriculture can influence hydrology—through increased wind and water erosion from cropping, and ground water withdrawal for irrigation and recharge from irrigation.

Agricultural activities typically result in increased surface water and wind erosion in the immediate area. This can result in a change in the water table by altering stream characteristics. Grazing can cause a change in water relations by removing the protective plant cover, as well as through soil compaction. Rain falling on fallow agricultural land disturbs the soil surface layer by breaking up aggregates and washing away loosened soil particles. The portion of rainwater that does not infiltrate into the ground is free to runoff over the soil surface, resulting in the formation of rills, runnels, and rivulets, and ultimately producing a variety of erosional forms. The most effective and least costly form of soil protection against erosion is the establishment of a good vegetation cover.

The presence of plant cover also reduces raindrop impact, evaporation from the soil, the formation of surface hard pans, and the destruction of the soil structure. Agricultural crops and grasses intercept from 5 to 30% of incoming precipitation before it reaches the soil (Shpak, 1971). This total is dependent on a number of factors including crop type and stage of development, density, severity of storm incidents, etc. Root systems of plants, especially perennial species, contribute to the maintenance of the soil structure by affecting the formation of aggregates, and by opening channels along the roots, which in turn enhance the infiltration of water into the soil. All forms of vegetation, including agricultural crops, protect the soil by providing a leafy cover over the surface, and by extending root systems into the soil, which loosen the soil and preserve the erosion–resistant properties of soil. Different agricultural crops vary in their effectiveness in resisting soil erosion. Mechanized cultivation techniques such as tilling, and terracing also play a significant role in determining the rate of soil erosion and water infiltration, as does crop rotation and other agricultural practices.

Waste burial sites located within areas where ground water is widely utilized for irrigation should consider the possible impact of irrigation by ground water. The use of ground water for irrigation can result in a regional lowering of the water table, thereby reducing the likelihood that a waste disposal site will be affected by water, however, increasing the likelihood of subsidence. Conversely, the cessation of wide–spread ground water irrigation might raise the ground water table resulting in a ground water problem at a nearby waste disposal site.

3.2.2 Forestry Practices. The primary concern with forestry activities involves the potential large–scale impacts that forestry practices can have on the local and regional hydrology. The existence of forests is recognized as an important factor in the water resources of the watershed. Closely involved with this is the importance of forests in protecting the soil from erosion, as forests represent the most effective protection against soil erosion. Tree roots greatly facilitate the movement of water within the soil. Trees also provide the overstory, which intercepts rainwater and snow. The interception of precipitation by tree crowns in forests ranges from up to 25% in mixed deciduous forests to up to 50% in spruce forests (Shpak, 1971). Within a given forest type, the interception of precipitation is dependent on the quantity and intensity of the precipitation as well as the density of the canopy. Forests also effect the extent to which precipitation water reaches the waterways because the forest is able to intercept and store large amounts of precipitation. Forests also play a small role in the distribution of precipitation. More precipitation falls over large forests than over surrounding non–forested areas (Shpak, 1971). Finally, forests play a significant role in avalanche prevention.

Any changes made in the forest canopy, even the elimination of individual trees, can result in a change in the degree to which precipitation is intercepted. Thinning operations can therefore impact the water budget in a watershed, and has been estimated to increase the fraction of precipitation reaching the ground by up to 25% (Reidl and Zachar, 1984). Timber cutting activities can drastically alter stream flows and sediment yields, causing downstream flooding. Streams can become clogged with logging debris, and associated logging roads can provide an additional source of erosion. Runoff has been shown to increase following logging, with the relative amount dependent upon a variety of factors, including the type and extent of logging conducted. Clearcutting has been estimated to increase runoff by up to 65% (Reidl and Zachar, 1984). Timber harvesting also impacts nutrient cycling both directly, through the removal of biomass from the site, and indirectly, through effects on the water relations, community structure, etc. Timber harvesting can also result in a change in forest type. For example, harvesting of eastern white pine (*Pinus strobus*) has historically resulted in the replacement of this forest type by mixed hardwood forests. Different tree species show marked differences in their influence on precipitation water; how much water they intercept or let through via throughfall or stem flow, how much is allowed to reach the ground, how much is returned in the evapotranspiration process, etc. Management of the forest in favor of a different tree species can therefore also result in an impact on the watershed.

The impacts associated with widespread deforestation are similar to those described above for timber harvesting, but can occur on a much larger scale. On a global scale, large–scale deforestation in the tropics appears to be influencing the global carbon cycle (see Section 3.3).

3.2.3 Energy, Water, and Mineral Extractions. Extraction of a resource from the subsurface, or mining, can be categorized according to several different criteria. What are now considered non–economical deposits may be in great demand in the future. Additionally, new technologies such as those associated with the electronics industry may create a demand for more transition elements or other elements not considered economic at this time. For the purpose of exploring the possible impact of mining on a LLWDF, the categories of surface mining or underground mining incorporating water and oil extractions are useful.

3.2.3.1 Surface Mining. Surface mines and quarries today cover less than 0.5% of the total area of the United States (Keller, 1976). Major surface mineral extraction industries (i.e., coal, phosphate, salts, etc.) are currently controlled by federal and state statutes (e.g., Surface Mining and Control and Reclamation Act of 1977 [SMCRA PL:9587]) and are therefore subject to a permitting/siting review that should preclude inadvertent intrusion into the LLWDF.

The regional environmental effects of surface mining are associated with regional precipitation and topography. For example, coal mining in the relatively dry and flat Great Plains region creates different problems than experienced in the coal mining region of Appalachia. The Great Plains and midwest coal fields are, for the most part, still within the stratigraphic orientation in which they were formed. This flat layering of the coal beds is conducive to open cut strip mining (area mining), which leaves behind a subsurface much different than what was present prior to the strip mining.

Environmental problems associated with Great Plains strip mining include the interruption of regional aquifers (coal seams); exposure of saline, sodic or acidic materials (a result of inverting the weathering sequence); increased erosion from the spoils; and degradation of ground water flowing through replaced spoils. Increased erosion and the disruption of regional aquifers are the most likely of these environmental problems to affect the performance design criteria of a LLWDF. Spoils can enter a stream through accelerated erosion causing an increase in the base level that could effect the 100 ympf assumptions. Coal seams in the Great Plains tend to have higher transmissivities that the surrounding rock. Interrupting the coal seam aquifer by mining it and replacing it with spoils of lower transmissivity could lead to an underground ponding effect that effectively raises the ground water level in the spoils area and/or changes regional ground water flow patterns.

Some open pit hard rock mining operations, such as the Bingham Canyon copper mine in Utah, which covers nearly 3 square miles, are also considered major surface mining operations. As the available high grade ore is rapidly depleted, the trend in recent years has been away from subsurface mining pursuing localized high grade ores to large, open–pit mines that are economical for lower grade ores (Keller, 1976). Regional examples of large surface mines are the taconite mines of the Northern Great Lakes region; the gold, silver and copper mines of the Rocky Mountain, Southwest, and Pacific Coast regions; the evaporite (trona, borax, magnesium, other salts) mines of the Rocky Mountain and Southwest regions; and the phosphate mines of the Southeast.

The relevance of open pit mining in an area adjacent to a LLWDF is the possible impact of large volumes of mostly toxic spoils and/or tailings as a contributor to the area's erosion–silting–stream baseline 100–year ympf siting assumptions. Many mining districts have extensive spoils and/or tailings slime areas that are devoid of natural cover due to the toxicity. These large open areas with fine unconsolidated materials are excellent sources of erodible materials and contribute to the flooding potential by reducing the retention time.

As for the possibility of the accidental mining of a LLWDF, the exploration and siting procedures associated with a major hard rock mining operation should preclude any possibility of a LLWDF being inadvertently disturbed.

3.2.3.2 Underground Mining. Underground mines are also associated with unique environmental problems. Surface subsidence, tailing piles, and acid mine drainage have been the most common problems at underground mine sites. Again, using coal mining as an example, the Appalachian region coal fields are different from those of the Great Plains and Midwest. Increases in topographic relief, rainfall, and stratigraphic orientations complicate the mining process. Most coal mining in the region was underground before the 1950's. Since that time, however, a form of strip mining termed "contour mining" has been favored (B. T. Lowe, 1983). While also encountered to a lesser degree in the Great Plains and Midwest regions, the legacy of Appalachian coal mining is relic spoils, coal seam fires, and acid mine drainage. Locally important floods from breached dams built from unstable spoil materials have occurred. Whole towns have been moved because of burning underground coal seams that create noxious gases and subsurface voids, which in turn collapse destroying building foundations. The siting of LLWDF's over coal seams, such as at the Sheffield LLWDF, could result in containment breaches due to a future burnout and collapse of the coal seam. Furthermore, shock waves from mine blasting nearby could damage the integrity of a LLWDF much in the same way as an earthquake.

Another form of underground mining that should be considered is the removal of liquids (oil and water) and in situ (salt brines, gas, and coal gasification) mining techniques. The main threat to a LLWDF from these types of extractions is subsidence.

Several localities have been affected in California, where ground water has been pumped from basins filled with alluvial sediments. More than 2000 square miles of the Los Banos–Kettleman City area of the central valley of California have subsided by more than one foot.

One 70–mile stretch has subsided an average of over ten feet with a maximum subsidence of 28 feet (Keller, 1976). Another important area of ground subsidence accompanying water withdrawal is beneath the Houston, Texas area. There, subsidence of one to three feet was observed across a 30–mile area (Strahler, 1977).

The Wilmington oil field in the harbor area of Long Beach, California is a good example of land subsidence cause by oil extraction. Subsidence was first noted at the site in 1940, and by 1974 subsidence had increased to 29 feet in the central area. Salt mining by solution produced a subsidence pit 400 feet across and 300 feet deep near Detroit, Michigan in 1970. Another salt mining operation produced a 250–foot diameter hole near Saltville, Virginia in 1970 (Keller, 1976).

The threat to the performance of a LLWDF from man–caused subsidence events is self–evident, as is the threat from natural subsidence events such as experienced in karst areas. The propensity of the public to invade a LLWDF for the purpose of reclaiming materials (even though they are radioactively contaminated) has already been shown at the Beatty, Nevada site. This type of illegal intrusion and the occasional operator looking for sand and gravel may be the greatest "mining" threat to the integrity of a LLWDF.

3.2.4 Urbanization. As large cities grow in size, their impact on the environment increases. Large cities can modify some of the climatological factors in the immediate area, resulting in a relatively small scale, but significant variations in climate on a micro scale. Increases in temperature in and around urban areas can occur due to a loss of evaporative cooling normally provided by vegetation and exposed soil, re–radiated heat from paved surfaces and buildings, and heat produced directly by industrial and other activities. Large urban areas can be up to 2°C warmer than nearby non–urban areas. Urban areas can also cause an increase in the amount of precipitation received downwind. This phenomenon results from airborne particulate matter originating in the urban area providing additional condensation nuclei for the production of precipitation downwind of the urban area.

Urbanization can also result in other types of impacts in the area surrounding a city. If the water supply of the city is drawn from ground water, significant changes in the local water table and in ground water flow may occur. Changes in the direction of ground water flow may also result. Roads and municipal waste sites associated with the city can also result in an impact on the area.

3.3 Influence of Climate Change

The potential influence of changing climate has been recognized for some time as an important issue for the management of high level radioactive waste (Barron, 1987; Goodess et al., 1990). This has been largely because of the long timescales under consideration for high–level waste disposal. The magnitude of the changes indicated by the paleoclimatic record over comparable periods of time include such dramatic events as massive glaciation and wholesale shifts in ecosystems. Indeed, one of the reasons for deep geologic disposal is to isolate waste from changing conditions for very long periods of time ranging from tens to hundreds of thousands of years.

Even though LLWDFs are concerned with comparatively short time periods of a few centuries, the potential influence of changes in climatic conditions are also relevant to the management of low–level waste. Near surface disposal facilities are much more tightly coupled than geologic repositories with the environment affected by climatic conditions. They are, therefore, more likely to be influenced by the less dramatic variations in climate that can occur over a few hundred years. In addition, recent concern over the "greenhouse effect" has raised the possibility that anthropogenic influences on climate could result in large, systematic shifts in climatic conditions.

Both natural climatic variation and possible anthropogenic climate change have the potential to alter site characteristics important to low–level waste site performance. Examples include those site characteristics that are related to site hydrology such as precipitation and evapotranspiration rates, that in turn determine percolation and recharge rates, surface water runoff, and erosion. Other examples include environmental conditions that affect the biotic component of the LLW site such as the sequence of plant and animal community succession that affects the performance of earthen covers and the potential for biotic intrusion. Climate can be viewed as a driving force that produces changes in site performance. These changes in performance are mediated by changes in the hydrologic and biotic components of the site environment. Over the period of interest, the only driving forces of comparable potential impact are those associated with changes in human land use patterns (Figure 1).

Addressing the potential influences of changing climate requires an understanding of the magnitudes and timescales of climate change, particularly possible anthropogenic change, as well as the relative sensitivity of different sites to these affects. This section will treat each of these concerns in order, beginning with a review of the historical record of climate change. The relative sensitivity of different sites will be treated by considering the potential impact of the greenhouse effect on the sites of the six existing LLW facilities.

3.3.1 Historical Patterns of Climate Change. The record of natural fluctuations in climate over recorded history provides an estimate of the potential magnitude of changes over the time period of interest to low–level waste disposal. It also provides an essential context for evaluating possible anthropogenic climate change due to the introduction of greenhouse gases to the atmosphere.

Evaluation of changing climate is complicated by questions of scale. The choice of a relevant timescale for this discussion is based on the period over which a low–level waste disposal facility must perform, roughly 100 to 1000 years. Systematic trends in temperature, precipitation, and related parameters over this timescale can be legitimately called changes in climate, while variation over shorter periods of one to ten years constitutes weather rather than climate. Paleoclimatic changes over the 10,000 to 100,000 year timescale are generally outside the scope of this discussion except to provide a context for the climate of the historical period.

For each of these timescales, evaluation of climate change is limited by the quality of the data available. Paleoclimatic data consist of various quantities that can be correlated with global annual mean temperature. These include O–18 (this is an isotope of oxygen) variations in ice cores and planktonic foraminifera in ocean sediments, distribution of flora and fauna in soils and sediments, and changes in elevation of timberline (Bolin, 1980; Flohn and Fantechi, 1984). Inferences about precipitation and other climatic parameters are drawn from these estimates of global annual mean temperature. These estimates of global climate can be related to near surface disposal facility performance only in the most general way. For the historical period, there are more direct measurements of climatic parameters, at least for the continent of Europe (Flohn and Fantechi, 1984), that can provide examples of changes that could be important to low–level waste disposal but are not relevant to any particular site. Typical site characterization data addresses only the record of weather over the last few decades and cannot support evaluation of climatic trends.

Discussion of climate change due to the greenhouse effect is faced with some of the same considerations as evaluation of paleoclimatic changes. The general circulation models currently used to evaluate global climate change scenarios can provide estimates of global mean annual temperature changes. They are far less reliable tools for estimating other climatic parameters such as precipitation, runoff, and evapotranspiration. General patterns of change can be estimated on a broad regional basis but these models are not capable of evaluating site–specific changes.

The last period of global glaciation reached a peak about 20,000 years ago (B.P.). At this time, the mean global temperature was about 4°C colder than today with a difference of 6 to 10°C in polar regions and about 2°C at the equator (Bolin, 1980). Extensive ice sheets covered northern Europe and Canada; pack ice around the Antarctic continent extended considerably further north. The lower average temperature was associated with a reduced intensity in the global hydrologic cycle because evaporation decreases with decreasing air temperature. A change of one degree implies a change in water saturation pressure of seven percent. The intensity of the hydrologic cycle is governed by evaporation in the tropics, which would have been about 15% less than it is today. The lower temperature and reduced hydrologic cycle resulted in a very different distribution of climatic zones and biomes from what exists today (Bolin, 1980).

The transition from the peak of glaciation to a warmer climate proceeded slowly for a period of about 6000 years and was followed by a very rapid series of changes that culminated in the post–glacial climatic optimum during the mid–Holocene (9000 to 5000 B.P.) (Bolin, 1980). The period preceding this climactic optimum is illustrative of the magnitude of sustained climate change that is possible over a timescale of a few thousand years.

During the mid–Holocene, the global average temperatures were between 1.5 and 2°C warmer than present (Kutzbach, 1987), roughly corresponding to the average increases predicted for the anthropogenic greenhouse effect. Evidence of the regional ecological, hydrologic, and climatic conditions of that period could provide proxy evidence for a variety of climatic variables of interest in evaluating the potential impact of anthropogenic climate changes. These parameters would include seasonal variation in temperature and precipitation (Fritts, 1976) and the distributions of plant and animal communities (Ruddiman and Wright, 1987).

The mid–Holocene climatic optimum is also illustrative of the wide regional variation in climate change effects. For example, at this time considerable parts of Canada were still ice–covered while Scandinavia was essentially ice free thus introducing an asymmetry in westerly winds. The resulting rainfall patterns produced prolonged moist periods in areas of the eastern Mediterranean and in Pakistan and northwestern India where the climate is arid or semi–arid today.

Following the post–glacial climatic optimum, a slow, irregular decline in global temperature took place. There was a brief warming during the late Middle Ages (800 to 1100 A.D.), followed by a further decline in temperature throughout the northern hemisphere that culminated in the Little Ice Age (1500 to 1700 A.D.). During the Little Ice Age, temperatures were the lowest since the last glaciation. They ranged 2 to 3°C lower than during the post–glacial optimum and 1 to 2°C lower than present temperatures. Recovery from the Little Ice Age has been marked by a gradual warming trend at all latitudes of the Northern Hemisphere throughout the year. This trend accelerated at the end of the last century and reached a peak in the late 1930s when the mean air temperature of the Northern Hemisphere was about 0.6°C higher than at the turn of the century (Budyko, 1982). From the late 1940s through the early 1960s, there was a brief pause followed by renewed warming up to the present. The decade of the 1980s has been the warmest on record and includes six of the ten warmest years on record (Schneider, 1989).

Beginning about 1000 A.D., data became available that allowed estimates of trends in various climatic parameters directly relevant to LLW site performance. Unfortunately, the best data sets are not directly applicable to sites on the North American continent but describe conditions in Europe and the Mediterranean (Flohn and Fantechi, 1984). This data is useful, however, to describe long–term trends in temperature, precipitation, shift of seasons, and water budget. It is particularly valuable for analyzing the range and variability of these parameters

The available data include: (a) proxy data that reflect the influence of climate; (b) historical reports of the character of individual seasons and some specific events such as floods, storms, and frosts; (c) regular weather observations without instruments; and (d) regular meteorological observations including instrument measurements.

One category of proxy data includes agricultural records of harvest yields, vintage dates, grain prices, and so forth. Examples of proxy data of a strictly fossil nature are pollen distributions in lake sediments, variation in tree growth rings, advances and retreats of glaciers, and isotopic ratios of oxygen in dated ice cores. There is a vast amount of data in this latter category that remains to be exploited. Even though ambiguities remain in the interpretation of these proxy data, the techniques for using such measures hold promise for obtaining climatic records for sites in areas not covered by historical reports or meteorological observations.

Historical documentary reports containing incidental reference to climate are widely scattered through a variety of sources. These data have been studied by Lamb and others to derive indices of wet and dry summers and of mild and severe winters in Europe from about 500 A.D. to the present (Lamb, 1984). These data provide useful corroboration of proxy data and data from meteorological observations.

Regular weather observations without instruments are available from about 1400 on. Sources include, for example, numerous ships logs in the archives of various nations. Continuous meteorological instrument records are available for stations in England and the European continent beginning about 1700.

The availability of accurate climatic data for Europe since 1000 A.D. has allowed extensive analysis of the Little Ice Age and the subsequent recovery of the European climate. This period is of particular relevance to the question of climate impact on LLW site performance. It illustrates a well documented, systematic change in climatic trends over a period of 200 to 300 years that had significant impact on land use patterns, particularly for agriculture. The period was characterized by lowered average temperatures, increased precipitation and runoff, reduced evapotranspiration, and significant increases in soil moisture. Moreover, the frequency of storms and floods increased throughout northern Europe.

The Little Ice Age also illustrates the effects of increased variability in climatic conditions characteristic of other periods of rapid change in climate. Year–to–year variation in seasonal extremes of temperature and precipitation was greater than in the centuries proceeding or following this period. The spatial variation in these effects was extremely non–uniform due to disruptions in global atmospheric circulation and resultant changes in storm tracks (Lamb, 1984).

During periods of climatic change such as the Little Ice Age, site characterization data based on a few decades of observations will not be sufficient to represent either the means or the variation in climatic parameters over a period of centuries (Karl, 1988). In addition, the intensity of design basis storms and floods may be underestimated and their recurrence intervals overestimated for periods of significant climatic change. Because there is no assurance that the next few centuries will not be as unsettled as the Little Ice Age, the possibility of more extreme conditions must be included when evaluating long–term performance of disposal facilities.

3.3.2 Global Warming and the Greenhouse Effect. Recent concerns over the potential for anthropogenic climate change raise the possibility of a prolonged period of unsettled climate that could affect the performance of LLW sites in a systematic way. The basis of these concerns is the acceleration of global warming due to emission of CO_2 and other greenhouse gases into the atmosphere (Schneider, 1989). Despite all the controversy surrounding the term, the greenhouse effect is a well established theory of atmospheric science. The difficulties arise in estimating global and regional climatic response to increased CO_2 concentrations.

Estimates of global response are based on numerical models and natural analogs of large climate changes. Many global climatic models (GCMs) have been built during the last few decades to solve equations describing the known physical laws of heat transport to the atmosphere, oceans, land masses, and ice sheets. The results are in general agreement that a doubling of the current CO_2 concentration would increase the average surface temperature between 2 and 5°C. The long–term consequences of such a change can be seen by comparison to the last glaciation (4°C colder than today) and the post–glacial optimum (2°C warmer than today).

This comparison raises the possibility of using mid–Holocene climatic optimum as an analogue for greenhouse effect. More precise information on climate change than that provided by GCMs could possibly be obtained from the paleoecological and paleoclimatic records of analogous climatic periods. Evidence of the regional ecological, hydrologic, and climatic conditions of that period could provide proxy evidence for a variety of climatic variables, such as seasonal variation in temperature and precipitation (Fritts, 1976) and the distributions of plant and animal communities (Ruddiman and Wright, 1987). This approach has been used in attempts to validate the predictions of GCMs but has not been applied to specific LLW disposal problems.

The major weakness of using past climates as predictive analogs for greenhouse effect changes lies in the rates of predicted anthropogenic change. For example, plant communities reach climax states in variable lengths of time depending on environmental conditions, but typically require decades or centuries to respond to major changes. Alternatively, regression of an ecosystem can often proceed quite rapidly under the influence of changes such as repeated frosts or drought years. Most greenhouse warming scenarios envision doubling of the current CO_2 concentration over the next 40 to 100 years, ensuring a transient condition that makes detailed prediction tenuous at best.

The prediction of global climate response to greenhouse warming is fairly well established. Regional response is much more difficult to predict. This is due, in part, to the crude treatment of biological and hydrologic processes in current GCMs but is also inherent in the complexity of the problem. The wide spatial variation in responses to the global cooling of the Little Ice Age, for example, can be explained in only the most general terms.

The regional predictions of GCMs are valuable in addressing impacts on LLW site performance primarily as a source of illustrative examples. They can show the magnitude of potential changes in various regions of the country. They can also help identify the relative sensitivity of different types of ecosystems to the kinds of changes predicted by greenhouse warming scenarios. The results of a calculation using the NASA General Fluid Dynamics Laboratory (GFDL) model are used in Section 4 as a basis for discussing the relative sensitivity of the six existing LLW sites to the effects of a CO_2 doubling scenario.

3.4 Direct Impacts on Community Structure

This section describes a wide variety of processes that can directly impact plant and animal community structure, but may not be directly related to either human land use patterns or climate change. These include wind, wildfire, the introduction of exotic species, pathogens and insect pests, and air pollutants.

3.4.1 Wind. Wind can contribute to changes in plant community structure in a number of direct and indirect ways. Wind plays a significant role in the dispersal of seeds and pollen of many plant species. Many pioneer species, which are the first to become established in a disturbed site, are wind–dispersed. Similarly, wind plays a crucial role in the spread of many plant pathogens and, to a lesser extent, insect pests. Locust outbreaks, for example, are strongly influenced by wind patterns and intensities, and many examples exist of fungal pathogens that disperse their spores through the action of wind.

Wind can also be an important factor in community structure in a more direct sense in certain systems. The location of timberline, for example, is partially dependent on wind. Wind also plays a significant role in community development in sand dune ecosystems, and is responsible for the desiccation of plants and soils by increasing evapotranspiration, as well as the degree to which soil is eroded. Through its effect on soil erosion, wind can contribute to a change in hydrologic conditions.

Local winds affect soil moisture and humidity, and play an important role in wildfire conditions and behavior. The drying action attributed to warm winter winds when soil moisture levels are low can result in drought conditions. Wind removes humid air from around the leaves and increases transpiration. Evergreens can dry out if they lose more moisture than they can absorb from frozen ground during the winter months.

Catastrophic winds such as tornados, hurricanes, microbursts, etc., can result in a significant disturbance in a system that can result in the reordering of the structure of the ecosystem. Shallow–rooted trees and trees with brittle wood can be uprooted or broken by strong winds resulting in a regression of the seral stage.

3.4.2 Fire. As with wind, fire plays an important role in the development and maintenance of community structure in a variety of direct and indirect ways. Fire can result in a disturbance that triggers the successional process, or can act to exclude certain plants or types of plants from successfully becoming established in a given area. Adaptations of plant species to fire vary significantly. Many trees are fire–resistant in that their bark is sufficiently thick as to allow the tree to survive all but the hottest ground fires. Such forests are thereby well adapted to frequent understory burning. Many plants regenerate by means of vegetative propagules originating from subterranean roots, which are capable of surviving fires of moderate intensity. This adaptation allows the plant to regenerate copiously following a fire. Such plants include many forbs, most grasses, and some important shrubs and deciduous trees. Other plant species are adapted to a fire periodicity of one event per life cycle, with fire playing an important role in some stage of development of the species. In the absence of fire, plant species that are not fire–adapted will ultimately out–compete and replace most fire–adapted species.

In most of the forests of the world, fire plays a critical role in the establishment or regeneration of the community structure. In these systems, frequent fires kill seedlings before they are allowed to mature. Charcoal layers found in soil profiles indicate that at least 95% of forests in the north–central United States and adjacent central Canada have been burned at least once (Maissurow, 1935). Similarly, forests examined in the southeastern portion of the country indicate that most of these forests have been also been subjected to fires (Komarek, 1972).

In other cases, fire allows trees to become established. In these types of systems, fire removes understory grasses and other plants, allowing tree seedlings to become established. In still other instances, some species are directly dependent upon fire for their successful establishment or regeneration. Jack pine (*Pinus banksiana)* in the Southeastern United States, and lodgepole pine (*P. contorta*) in the Northern Rocky Mountain area produce high proportions of serotinous cones that open to release seeds only when the resins that hold the cones closed are melted.

Extensive pre–settlement grassland fires are also believed to be the primary reason why the Great Plains of the central United States are to a large degree treeless. These fires were not unusual occurrences, but represented a natural and integral part of most grassland environments prior to the arrival of European man (Gleason, 1913; Humphrey, 1962; Cooper, 1961). Environmental extremes as expressed by fluctuations in rainfall and/or temperature tend to promote the establishment and expansion of grasslands at the expense of woody tree or shrub systems. Woody tree or shrub systems survive best under more stable environmental conditions. Recurring disturbances, such as fire, favors the establishment and perpetuation of grasslands and savannas in regions having climates capable of supporting brush or forest. Woody plants typically have difficulty invading established grasslands if the grassland is subject to recurring fires. In many grassland systems in the United States, grazing has replaced fire as a recurring disturbance process. Grasslands typically survive and often thrive on extremes such as strong winds, extensive dust storms, violent thunderstorms, hail, tornados, blizzards, and fires (Kozlowski and Ahlgren, 1974). Grasslands also provide their own ignition source, as well as an abundance of fine fuels. Burning has been found to generally increase the production of most grassland vegetation, but it may be deleterious to individual species of plants. Reaction of the system to fire varies with grassland type, fuels, soils, moisture conditions, fire frequency, and burning times (Kozlowski and Ahlgren, 1974). The removal of litter promotes the development of denser new growth.

Over the past century, when national fire policy dictated that all wildfires be suppressed immediately, the ranges of trees in several different geographic areas have expanded. This includes expansion of the pinyon/juniper forest type in the Southwest and Great Basin areas, the expansion of pine forests in the eastern coastal plain, and the expansion of mixed hardwood forests in the Ozark mountain area. Prevailing theory as to the cause of these expansions is that the reduction in fire frequency has allowed for the successful establishment of trees into the new areas. Similarly, fire suppression policies have been implicated in the expansion of the range of mesquite, a woody shrub, into former grassland areas in southern Texas. Chaparral systems are largely fire–induced communities. These systems typically are characterized by shallow soils, low surface soil fertility, and low water holding capacities. Shrubs of this community type typically regenerate by sprouting from underground following a fire. Deserts are less affected by fires than other systems, however, due primarily to the paucity of available fuels. Fire can still play an important role in these ecosystems.

Fires effect the nutrient status of soils, making some important nutrients more readily available while decreasing the availability of others. Burning results in great losses of total nitrogen from the site, while simultaneously increasing the mineralized nitrogen. The importance of losses of other nutrients resulting from fire depends on the properties of the soil, notably, the initial concentrations of the individual nutrients in the soil.

As fire policies change, large areas may become affected by influences of fire on the structure of the plant community. As with other disturbances, this could result in the invasion of a low–level radioactive waste site by species not historically found at the site. These species could have different properties with respect to how they could affect the long–term performance of the site.

Wildfires are not the only type of fires to which a site may be subjected. In some areas, prescribed fires are sometimes used as a management tool. For example, fire has been used to manipulate watershed areas in Arizona such that water and timber yield were increased, forage for game and livestock was improved, and soil erosion was reduced (Arnold, 1963). Conversion from shrub to grassland in California through the use of prescribed burning has resulted in increased water yields, and other examples of the use of prescribed burning as a management tool exist (Kozlowski and Ahlgren, 1974).

Another way in which fire could impact a waste burial site is through its effect on the water table. If large areas are allowed to burn (or conversely, if large areas that are naturally subject to periodic burns are prevented from burning), the height of the water table could be altered. If the water table underlying the waste disposal site were raised or lowered significantly, the integrity of the waste disposal unit could be affected.

The impact of fire on a low–level radioactive waste disposal site would most likely be dependent on other factors as well. Climatic factors such as increasing temperature and/or decreasing precipitation could contribute to the onset of significant fire event. Similarly, an introduced pathogen could kill the majority of vegetation in a large area, causing a buildup of a heavy fuel load ultimately resulting in a catastrophic fire. Fire frequency and intensity are also very much dependent upon patterns of land use.

3.4.3 Introduction of Exotic Species.

The absence of an organism within a given geographic area can often be attributed to the fact that the species has simply failed to reach the area. Over the 500 year timeframe, an area may be subject to a number of new plant and animal invasions. These introductions could be due to the intentional or unintentional actions of man, or could be independent of human activities. The success of an introduced species appears to be dependent on a number of interrelated factors (Ehrlich, 1986). These include the following characteristics of the invading species:

1. Abundant range in its native location
2. Polyphagous feeding habit
3. Relatively short generation times
4. Significant genetic variability
5. Fertilized female capable of colonizing alone
6. Larger than most closely–related species
7. Association with human activities
8. Adaptable to a wide range of physical conditions.

The degree to which the invading species alter the structure of the community is highly variable. In the most extreme case, the introduction and establishment of a new species would completely alter the previously existing community. A number of historical examples of the impact of introduced plant and animal species have been well documented.

Perhaps the best example of the potential for increasing the geographical range of an introduced species is that of the European starling (*Sturnus vulgaris*). After failing to become established in North America during several attempts, the European starling was finally successfully introduced in New York City during the last decade of the nineteenth century. This bird species is now found throughout the continental United States as well as much of Canada and parts of Mexico. Similarly, the house sparrow (*Passer domesticus*) was first introduced to the Eastern United States from Asia during the mid–nineteenth century. Since its introduction, the sparrow has expanded its range to include virtually all of the continental United States. Extensive ranges also currently exist in South America, Southern Africa, Australia, and New Zealand, all of which resulted from intentional introductions of the sparrow. Although the ecological impacts due to the European starling and house sparrow have probably been minimal, the impressive expansion of their ranges illustrate the potential for significant impact from the introduction of exotic species once the species has successfully circumvented the original barrier preventing it from entering an area.

The North American coyote (*Canis latrans*) offers a good example of a large mammal that has undergone a significant expansion of range during historical times. Originally restricted to the western portions of the United States and adjacent Canada and Mexico, the coyote is now a transcontinental species, with populations successfully established as far east as New England and the southern Appalachians. In the expansion of this species, man has played an unplanned, but critical role by providing suitable habitat for the coyote while reducing competition with competitors such as the grey and red wolves.

An example of an introduced animal species that did result in a significant impact to an existing ecosystem is the introduction of rabbits to Australia. Because no natural predator existed in Australia to help control the rabbit population once it became established, the rabbit population increased unchecked. The rapidly increasing rabbit population resulted in a severe reduction in the quality of Australian range. No only did this impact the success of the Australian sheep and cattle industries, but several species of native herbivores were also impacted, which could not compete with the growing populations of rabbits. After undergoing several cycles of population growth and crashes due to their exceeding the carrying capacity of their new habitat, rabbit populations in Australia were finally controlled through the introduction of a virulent strain of a mosquito–borne virus that causes the disease myxomatosis in rabbits.

Human commerce and travel have had a significant impact on the distribution of plant species over the past century or more. In North America, significant alterations in habitat distribution by humans have allowed some relatively benign native plants to become important weeds with expanded distributions (Baker, 1986). Some ecosystems are more vulnerable to invasions than others. Among the most likely systems to be impacted include grasslands, especially when overgrazed (Baker, 1986). The total impact of nonnative plant species on community composition and structure can be significant. In 1939, for example, introduced plants in the San Joaquin Valley in California were estimated to comprise 63% of the herbaceous vegetation of the grasslands, 66% in woodlands, and 54% in the chaparral (Talbot et al., 1939). Other ecosystems such as dense forests, high montane systems, salt marshes, and deserts appear to be relatively resistant to invasion.

A number of introduced plant species have become localized pest species. These include kudzu (*Peuraria lobata*) and lespedeza (*Lespedeza spp.*), vine species introduced into areas of Southeastern United States as pasture crops and have become problems by out competing native plants and, in the case of kudzu, killing trees and shrubs. In the northern plains region of the U.S., several plants have been imported for use by honeybees, and have since become an undesirable rangeland species. Introduced Russian thistle (*Salsola kali*) has also been classified as an undesirable range species. Various aquatic plants have become problems in canals and other water bodies in and around Florida, including alligator weed (*Alternanthera philoxeroides),* water hyacinth (*Eichhornia crassipes*), and kariba weed (*Salvinia molesta*) from South America (Barrett, 1989). These species have been responsible for clogging canals and other water channels, and require a large annual budget to ameliorate their effects. Similarly, a native North American waterweed (*Elodea canadensis*) has caused problems in Great Britain since being introduced there in the mid–nineteenth century. Even tree species are included in the introduction of undesirable species. These include the intentional introduction of melaleuca (*Melaleuca quinquenervia*) and schinus (*Schinus terebinthifolius*) into Southern Florida. The purpose of these introductions was an attempt to convert the Everglades to forest.

Although the impacts of these and other introduced plants and animals have not resulted in impacts such as might be required to affect the performance of a waste disposal site, it can be assumed that the potential for such an occurrence exists in the 100 to 500 year timeframe.

3.4.4 Pathogens and Insect Pests. As with the introduced exotic plant and animal species, introduced insect pests and pathogens are capable of altering the structure of a community. Because host organisms have not been subjected to these agents, they are often extremely susceptible to the effects of the invading organism. The results are often devastating. An estimated 40% of all insect pests to agricultural systems in the United States are introduced species (Pimental, 1986). Furthermore, parasites and predators are often introduced as biological control mechanisms for various insect or weed pests, many of which have been inadvertently introduced themselves (Hokkanen and Pimental, 1984). Several such attempts are usually required before an effective biological control is found, if one is ever found.

Perhaps the best example of the effects of an introduced plant pathogen is that of the tree disease known as chestnut blight. In the early part of the 1900s, the American chestnut (*Castanea dentata)* was one of the most important components of the Eastern hardwood forest. The natural range of the chestnut extended from northern New England south to Georgia and west to southern Illinois. Up to 40% of the trees within much of this area was comprised of chestnuts. The chestnut was important from both ecological and commercial standpoints. Uses of the species included timber production, nuts for both wildlife and humans, and as an important source of tannin. Around the turn of the century, a fungal pathogen *Endothia parasitica*, was introduced from Asia in nursery stock in the New York City area. This fungus, to which native chestnuts had no resistance, caused a devastating disease called chestnut blight, which over the next few decades virtually wiped out American chestnut throughout its entire range.

Other examples of devastating imported forest pathogens include Dutch elm disease (*Ceratocystis ulmi*), which has had a tremendous impact on native elms, and white pine blister rust (*Cronartium ribicola*), which has caused similar problems on a number of North American white pines. In each of these cases, the affected tree species did not occur in pure stands, so that individuals of other tree species present in the area were able to replace the affected trees, thereby minimizing the impact on the system as a whole. If such a devastating disease were to attack a species that forms extensive, pure stands, however, replacement by other tree species would be at best delayed, while the new species migrated into the affected areas. Areas such as the northern boreal forest which is dominated by two closely–related species of spruce, and areas in the Rocky Mountains where fairly extensive pure stands of ponderosa pine (*Pinus ponderosa*) or lodgepole pine (*P. contorta*) occur could be impacted in a devastating manner should such a disease result in a rapid, wide–spread eradication of one of these species. Such an occurrence would result in the establishment of an entirely new community structure, which may or may not include trees, and which might impact the performance of a waste site in a number of different manners. If the forest die–back was extensive, the ground water table could be affected.

With respect to insect pests, a good example is the gypsy moth (*Lymantria dispar*). The gypsy moth was introduced in Massachusetts in 1869 along with several other insects to crossbreed with silk–producing moths in an effort by the silk industry to develop disease–resistance. Within twenty years of its introduction, the gypsy moth had become a significant problem in New England, where severe outbreaks can completely strip foliage from trees and shrubs. A total of over 500 species of trees and other plants are ingested by the gypsy moth caterpillars, including most of the more important deciduous tree species in the Eastern U.S. Attempts to control the gypsy moth have resulted in the introduction of at least 40 natural enemies, ten of which have become established (Nichols, 1961). This is in addition to some 90 native natural enemies known to attack the gypsy moth (Campbell, 1975). None of these introduced or native organisms have yet been effective in controlling the gypsy moth, which remains a significant problem in northeastern forests.

In addition to introduced insect pests, native insects can become serious pests if the system is disturbed. For example, Douglas–fir tussock moth, eastern spruce budworm, southern pine beetle, and oak leaf–roller are all examples of indigenous insects that only became serious forest pests upon the cessation of natural and anthropogenic controls such as harvesting and wildfires. These insects provide examples of how human activities can have a significant indirect impact on natural systems.

3.4.5 Air Pollutants. The importance of air pollutants on LLWDFs is related to their potential impact on forest systems and their subsequent effect on the hydrologic conditions of the site. As with any large–scale deforestation resulting from timber harvesting, conversion of forests to agricultural use, wildfires, or infestation by forest pathogens or insect pests, the destruction of large areas of forest might result in significant changes in ground water and surface water characteristics. Air pollutants can also be related to both changes in land use and climate. As human land use patterns change, the patterns of deposition of air pollutants will also be expected to change. Carbon dioxide and other potential air pollutants have been implicated with the so–called "greenhouse effect" associated with global climate change. Discussion of the impacts associated with air pollutants is included in this section because severe air pollution damage can result in similar impacts to plant community structure and hydrologic conditions as those resulting from factors such as wildfires, insect, and pathogen infestations.

The impacts to forests associated with airborne pollutants is well documented (Smith, 1985; Tomlinson, 1983; Johnson and Siccama, 1983; Shepard, 1985). The pollutants that are of the most concern are oxides of nitrogen and sulfur, which serve as precursors to acidic deposition, although ozone and other materials may be of local importance in some areas. The sources of sulfur dioxide emissions in the United States include electric utilities (66%), industries (22%), metal smelters (6%), homes and businesses (3%), and transportation (3%), whereas nitrogen oxide emission sources include transportation (44%), electric utilities (29%), industries (22%), and homes and businesses (4%) (Postel, 1984).

The most severe cases of wide–spread forest decline have been observed in northern Europe where large areas of forests have died back (Schutt and Cowling, 1985). Although the exact mechanism by which this decline occurs is not certain, acidic deposition is presumed to be at least a significant contributor. In many locations in Europe, large numbers of trees over wide geographical areas have been killed. In many cases, the herbaceous vegetation associated with the trees has also been destroyed.

In addition to the direct effects of the pollutants, trees damaged by pollutants are often more susceptible to infestation by pathogens or insect pests, drought, frost, and other stress factors. Although most of the forest decline in the United States to date has been observed in the mountains of the eastern portion of the country (Johnson and Siccama 1985; Johnson et al., 1982), the American West is not immune to this problem (Roth et al., 1985).

3.4.6 Solar Radiation. Changes in solar radiation can impact plant community structure independent of other important climatic changes. Solar radiation is the factor that exerts the most direct control over the rate of primary production (food) in natural communities. This is true of both terrestrial as well as aquatic systems. The importance of light in natural communities is twofold. First, light provides the stimulus for the timing of daily and seasonal rhythms in both plants and animals. Processes affected by light include breeding, hibernation, estivation, and feeding in animals as well as pollination, seed set, senescence, and storage of food reserves in plants. The second indication of the importance of light is that it is essential to the process of photosynthesis, upon which all major food chains are ultimately dependent. Plants vary in their requirements for solar radiation, with some plants needing direct sunlight in order to complete some critical stage of their development while others require shade throughout their life cycle. Generally, shade–tolerant species have lower photosynthetic rates, which result in slower growth rates than do shade–intolerant species. The ecological limitations of plants can often be attributed to adaptations in the light regime of their habitat. Changes in the light regime to which a plant species is exposed can result in the failure of the species to perpetuate itself either by affecting the reproductive abilities of the plant or by killing the plant outright. Such changes could result in the disruption of the entire community structure through subsequent changes in food webs and habitat availability.

Changes in solar radiation levels can therefore result in the establishment of an entire new set of plants and animals at a site. If succession occurs at a radioactive waste disposal site, the new plants and animals inhabiting the site might cause more of an impact on the integrity of the site. This is especially relevant if the new community includes plant species with deeper root systems or animals with more extensive burrowing activities. Furthermore, alterations in erosional patterns might occur.

It is likely that any significant change in solar radiation input on a large scale would be accompanied by a number of other factors. These factors could include changes in temperature profile, moisture levels, wind patterns, etc. The causal agent for these changes could also result in a direct impact on the plants and animals. Causal agents could include various airborne pollutants, agricultural, mining, or forestry practices.

3.5 Summary

Individual organisms may exhibit metabolic or physiological responses to variations in climatic conditions, provided that such variations are of restricted amplitude within the boundaries defined by the organism's tolerance limits. Tolerance limits are related to the environmental conditions, in general, those conditions related to temperature, at which the enzyme complex of an organism functions at an optimal level. Because enzymes instructions are carried in the DNA/RNA of a species, tolerance limits are ultimately genetically determined. As tolerance limits have evolved in adaptation to the prevailing temperatures present in the habitat of the organism, they are not necessarily constant within a species. In general, the main manifestation of the response of a particular species to a climatic change is an adjustment of the distributional range of the organism.

Predictions regarding the future conditions at a waste disposal site (or other type of site) are often hindered by insufficient knowledge of future scenarios. Site characterizations that include predictions of future conditions are typically based on the best knowledge available, but this information may not prove to be accurate over the long–term timeframe. It is possible that after the 100 year institutional control period, the community structure at a waste disposal site will be significantly different from that which was expected at the time the site was established. Similarly, the hydrologic conditions at the site may not conform to predictions. If this is the case, a second characterization would probably be necessary in order to ascertain how the site may be affected beyond this period. At this time, an additional 100 year data base would be available from which to answer the questions listed above. The primary advantage of conducting a second characterization study at the end of institutional control is the inherent stability of the site may be more readily determined. If the conditions at the site have changed dramatically during the operational lifetime and post–closure institutional control period of the facility, it could become evident that assumptions drawn from the initial characterization study may not be acceptable under present conditions found at the site. If this is the case, the answers to performance questions will be much more difficult to ascertain.

4. APPLICATION TO EXISTING COMMERCIAL SITES

The purpose of this section is to discuss the factors described in previous sections in terms of their application to the six existing commercial low–level radioactive waste disposal sites located at West Valley, New York; Barnwell, South Carolina; Maxey Flats, Kentucky; Sheffield, Illinois; Hanford, Washington; and Beatty, Nevada. These sites represent six very different ecological settings. While they do not represent all possible sets of site characteristics, they do provide examples of locations that exhibit a wide range of vulnerability to the processes discussed in Section 3. In addition, there is an established base of experience at each location that is directly relevant to LLW disposal site performance even though disposal practices have undergone significant changes since these sites were established. If these sites are treated as full–scale experiments in LLW disposal, they will provide useful illustrations of potential long–term behavior.

Environmental processes were identified that might reasonably affect a LLWDF under the recommended NRC 500 year post–closure guidelines derived from 10 CFR 61. The processes were categorized into four major groups as follows: ecological processes, climatic processes, geologic/hydrologic processes, and anthropogenic processes including land use patterns (Figure 2). Each process listed was then evaluated for its potential to impact the LLWDF performance over the 500 year period. Additionally 210 years was evaluated as a possible LLWDF performance period of interest. This period was chosen to reflect data showing an inflection point in post-closure radionuclide inventories resulting from decay of nuclides with half lives of 30 years or less.

4.1 Establishing Baselines and Ranking the Sites

The available literature on the six extant commercial LLWDFs was examined to establish a data base for future modeling input parameters. The purpose of this section is to provide a summary of the results of this review. Tables 3 and 4 summarize the extent of known radionuclide migration at U.S. facilities. The three closed facilities (Maxey Flats, Sheffield, and West Valley) were especially valuable for their information on postclosure care requirements. The three operating facilities (Beatty, Richland, and Barnwell) were utilized to evaluate what effect current waste segregation and compaction procedures will have on future closure. Current improvements in waste segregation and compaction procedures will eventually affect closure by improving the possibility of waste retrieval when necessary and by decreasing the complications caused via subsidence.

Each of the previously mentioned environmental processes were ranked using an importance value scheme. This scheme involved assigning two numbers to each ecological process. The first number represented the probability of the event occurring, and the second number represented the significance the ecological process might have on the ultimate health of a population near the LLWDF should the event occur. The processes were ranked from zero, for low probability or low significance, to 10 for highly probable or significant impact. An overall importance value was generated from the two tiered ranking system by multiplying the two components probability and significance. The resultant data tables, Table 5, Importance Values, Table 6, Probability Values, and Table 7, Event Significance Values, show the processes as they were ranked for the six commercial LLWDF's. This ranking provided the basis for the identification of regional climatic, ecological and land use trends previously reviewed. Knowing what has happened these first years after closure at extant LLWDFs will facilitate the process of identifying important monitoring variables and design criteria for eventual no–maintenance closure of the LLWDF sites.

Table 3. Radionuclide migration at the U.S. commercial burial sites

	West Valley	Maxey Flats	Barnwell	Sheffield	Beatty	Richland
Extent of tritium migration observed	On– and off–site surface water; on–site ground water	On– and off–site surface water; on–site ground water	None[a] Possible percolation of trench water	On–site lateral migration in ground water	None[a] Possible vapor diffusion in soil	None[a] Possible vapor diffusion in soil
Extent of other radionuclide migration observed	On– and off–site surface water	On– and off–site surface water; on– and off–site ground water	None observed	None observed	None observed	None observed
Transport media	Surface contamination carried by run–off Water infiltration of trenches and overflow Effluent from liquid waste treatment Possible ground water transport	Surface contamination carried off by run–off Atmospheric release of tritium from the liquid effluent evaporator Ground water transport	None indicated	Ground water	None indicated	Tumbling tumble–weeds rodent excreta and carcasses
Potential causes for future problems	Loss of surface water control Subsidence leading to cover failure Ground water infiltration	Loss of surface water control Subsidence leading to cover failure Ground water infiltration	Loss of surface water control Subsidence leading to cover failure Rise of water table	Loss of surface water control Subsidence leading to cover failure Rise of water table	Dramatic climate changes Uncontrolled plant growth	Dramatic climate changes Uncontrolled plant growth

Table 3. (continued)

	West Valley	Maxey Flats	Barnwell	Sheffield	Beatty	Richland
Solutions or preventions	Surface water control Possible engineered ground water control Remedial action during period of cover subsidence	Surface water control Possible engineered ground water control Remedial action during period of cover subsidence	Surface water control Remedial action during period of cover subsidence	Surface water control Remedial action during period of cover subsidence	Natural conditions sufficient	Plant species and hypogeal animal controls

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a. Environmental surveillance may be insufficient for detection of all modes of migration.

Table 4. Radionuclide migration at the major Department of Energy burial sites

	Savannah River	Oak Ridge	Los Alamos	Idaho	Hanford
Extent of tritium migration observed	On–site ground water	On– and off–site surface water; on–site ground water	On–site vadose zone	None	None from solid waste burial ground
Extent of other radionuclide migration observed	None detected	On– and off–site surface water; on–site ground water	None detected	On– and off–site surface water, resuspension by wind, rodents	Uptake by deep rooted plants (tumbleweeds) and by rodents
Transport media	Ground water	Overflow from water filled trenches, ground water, surface water	None observed	Floods windborne rodent excreta and carcasses	Tumbling tumble–weeds, rodent excreta and carcasses
Potential causes for future problems	Loss of surface water control Subsidence leading to cover failure Ground water infiltration	Continued uncontrolled surface and ground water; Subsidence water; Subsidence leading to more cover failures	Dramatic climate changes	Surface water infiltration and movement through fissured formations	Uncontrolled plant growth Dramatic climate changes
Solutions or precautions	Surface water control Remedial action during period of cover subsidence	Engineered surface and ground water control Exhumation Remedial action during period of cover subsidence	None necessary	Surface water control Remedial action during period of cover subsidence	Plant species and hypogeal animal controls

Table 5. Importance values

Commercial Low–Level Waste Disposal Facility	Commercial Low–level Waste Disposal Facility Environmental Decision Matrix											
	Animal Invasion	Plant Succession	Ground Water Transport	Erosion	Compliance Monitoring	Vertical Soil Monitoring	Global Pollution	Agricultural Processes	Mining Energy Extraction	Urbanization	Seismic Processes	Volcanic Processes
Maxey Flats, Kentucky	72	80	54	72	50	21	20	15	9	6	27	0
Richland, Washington	90	60	45	42	40	20	18	20	9	12	27	15
West Valley, New York	72	80	81	72	40	28	27	15	36	24	18	0
Barnwell, South Carolina	63	80	70	72	40	30	45	20	9	10	36	0
Beatty, Nevada	81	40	28	42	28	5	36	18	9	5	27	10
Sheffield, Illinois	72	60	63	54	50	36	18	15	27	6	9	0

Table 6. Probability values[a]

Commercial Low–Level Waste Disposal Facility	Commercial Low–level Waste Disposal Facility Environmental Decision Matrix											
	Animal Invasion	Plant Succession	Ground Water Transport	Erosion	Compliance Monitoring	Vertical Soil Monitoring	Global Pollution	Agricultural Processes	Mining Energy Extraction	Urbanization	Seismic Processes	Volcanic Processes
Maxey Flats, Kentucky	8	10	6	8	10	7	10	5	1	3	3	0
Richland, Washington	10	10	5	6	8	5	9	4	1	3	3	3
West Valley, New York	8	10	9	8	8	7	9	5	4	4	2	0
Barnwell, South Carolina	7	10	10	8	8	6	9	5	1	2	4	0
Beatty, Nevada	9	8	4	7	7	1	9	2	1	1	3	2
Sheffield, Illinois	8	10	7	6	10	9	9	5	3	3	1	0

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[a] The probability value is an estimate of the likelihood that a site will be perturbed by the specific event sometime in the 300 year post–closure time period. The scale is from 1 to 10 with 10 being an assured event.

Table 7. Event significant values

Commercial Low–Level Waste Disposal Facility	Commercial Low-level Waste Disposal Facility Environmental Decision Matrix											
	Animal Invasion	Plant Succession	Ground Water Transport	Erosion	Compliance Monitoring	Vertical Soil Monitoring	Global Pollution	Agricultural Processes	Mining Energy Extraction	Urbanization	Seismic Processes	Volcanic Processes
Maxey Flats, Kentucky	9	8	9	9	5	3	2	3	9	2	9	5
Richland, Washington	9	6	9	7	5	4	2	5	9	4	9	5
West Valley, New York	9	8	9	9	5	4	3	3	9	6	9	5
Barnwell, South Carolina	9	8	7	9	5	5	5	4	9	5	9	5
Beatty, Nevada	9	5	7	6	4	5	4	9	9	5	9	5
Sheffield, Illinois	9	6	9	9	5	4	2	3	9	2	9	5

4.2 Examples of Chronic Change from the Six Commercial Sites

The six commercial sites could be considered "full–scale" experiments. Data on long–term low–intensity change and short–term, low–probability, high–intensity change experiences at the sites should be evaluated before any future sites are licensed. This section selects recent events or reports from the six commercial sites as examples of real or future ecological consequences. The subjects are divided into four categories: ecological processes, climatic processes, geologic/hydrologic processes, and anthropogenic processes (land use) to parallel our conceptual model of factors that could affect a LLWDF (Figure 2). Discussion of the different topics is in the same approximate order as they are found in Tables 5, 6, and 7.

4.2.1 Ecological Factors. Ecological factors are those plant and animal influences that a LLWDF might be subjected to over the 500 year service life of the site. Animal invasion is more of a problem at the drier sites (Richland and Beatty) because of limited above–ground resources available to the animals. In arid regions, animals (ants, squirrels, gophers, moles, rats, mice, coyotes, badgers, rabbits, burrowing owls, etc.) are more likely to be subterranean at some point in their life cycle because of the limited amount of above–ground cover and nesting materials available, and the need to be protected from environmental temperature extremes. Mammals such as jackrabbits, badgers, and coyotes seeking salt (cesium salt cake) have already caused problems at some of Hanford's other waste disposal sites. Other burrowing animals (pocket mouse, burrowing owl, reptiles, etc.) have been encountered seeking nesting materials at desert sites. It is estimated that one colony of ants is capable of moving 150 kilograms of soil per annum at the Richland LLWDF. These burrowing animals have the potential for disrupting the cap and bringing low–level waste to the surface via particulates. The burrows break the integrity of the trench cap allowing surface water to infiltrate. Consumption of contaminated geophagous macroinvertebrates (e.g., worms) could also be a potential problem. A shrew or mole can consume up to three times their weight of prey in a day. These animals can bypass the cap system from outside boundaries and spread radionuclides.

Plant succession is more of a problem at the humid sites (Barnwell, Maxey Flats, Sheffield, and West Valley). This is because LLWDF sites are located in non–floodplain areas by NRC regulations thereby eliminating deep rooted phreatophytes in favor of shallow lateral rooted species such as creosote brush, *Larrea tridentata* at the arid sites. At the humid sites, ecological succession is going to happen, unless a disclimax is maintained. Cornam (1979) reports on the operating experience at a Savannah River burial ground (Barnwell). In his report he states, that "uptake by vegetation is one of the most common routes for dispersal of radioactivity." Ten incidents of vegetation contamination were observed between 1965 and 1975. The radioactivity levels in the vegetation were of the order of a microcurie per gram of vegetation or less.

Plant succession is yet to occur at West Valley and Barnwell. The sites are currently being maintained at a grassland type disclimax by mowing and other measures to prevent introduction of higher successional order woody species. Larger plants have larger root masses with the capability of penetrating the trench cap and creating access to buried material. The low–level waste can be transported to the surface via evapotranspiration or guttation, an upward pumping action. Surface water can also run in along root channels and thereby increase the transport rate of waste to the ground water.

4.2.2 Climatic Processes. The potential for adverse impact on site performance due to changing climate varies significantly over the six sites. This is a consequence of two interacting factors at each location: (1) the baseline climatic conditions and the degree of variation associated with them and (2) the magnitude of the changes that can be anticipated in the future. This is illustrated by the results of modeling calculation made using the NASA General Fluid Dynamics Laboratory

(GFDL) global climate model. Estimates of changes in average summer and winter temperature and summer and winter precipitation were made for the continental United States under the assumption of a doubling of atmospheric CO_2 concentrations. Values for regions containing each of the six LLW sites appear in Table 8.

This GFDL calculation must be treated as an example scenario rather than an attempt at reliable prediction. It serves to illustrate the magnitude and direction of changes that can be anticipated using the current understanding of the problem. The general results of modeling exercises of this type are fairly consistent with respect to average annual and seasonal temperatures. They indicate warmer summers and winters throughout the continent with increases ranging from 2 to 6°C. The interior of the continent would see generally larger increases than the coastal areas. Estimates of precipitation changes are much more variable. In the scenario presented here, winter precipitation would increase in the upper Midwest and Northeast, decrease in the Southeast and eastern seaboard, and remain essentially unchanged west of the Rocky Mountains. Summer precipitation would decline in the plains states, the Southeast, the Northwest, and the eastern seaboard but remain unchanged elsewhere.

Changes of the magnitude of those shown in Table 8 may appear small and are certainly well within normal year–to–year variation. However, because they represent potential changes in long–term, average conditions they would produce significant impact on plant succession and land use patterns, particularly those associated with agriculture. Higher temperatures and lower precipitation would increase the frequency and intensity of droughts and the rate of wind driven erosion in arid locations. Areas subject to fire might see an increase in fire frequency with resulting impacts on plant succession. Over sufficiently long periods decreased precipitation and increased evapotranspiration would reduce ground water recharge and affect regional hydrologies.

Arid sites such as Beatty and Hanford would see smaller direct effects from changes in temperature and precipitation because they have comparatively slow baseline hydrologic cycles. Some humid sites, such as Barnwell, may actually see an improvement in site performance due to reduced precipitation and potential percolation. Sites in the Midwest such as Sheffield and Maxey Flats may have to adjust performance assessment estimates to account for increased seasonal precipitation. Long–term changes in precipitation may also affect the intensity of maximum possible floods and the recurrence interval for design basis floods.

All sites would have to be evaluated for their potential for changes in species survival and subsequent plant and animal life invasions due to slightly altered habitat conditions. Corresponding effects on agricultural practices including irrigation and its impact on regional hydrology could be important, particularly for humid locations.

Table 8. GFDL model estimates of climatic parameters for doubled CO_2

	Temperature Increase (°C)		Percent Precipitation	
Location	Winter	Summer	Winter	Summer
Barnwell	3.4	6.3	77	44
Beatty	4.6	7.3	105	77
Hanford	4.3	5.3	92	57
Maxey Flats	5.0	6.6	123	87
Sheffield	4.7	6.1	140	84
West Valley	6.9	5.0	101	84

4.2.3 Geologic/Hydrologic Processes. Ground water transport has occurred at most of the sites (Tables 3 and 4). Ground water transport will occur more often at the humid sites because of the greater availability of infiltrating ground water, and the closer proximity of the water table relative to the LLWDF. The attempt to limit ground water transport in humid areas by locating the trenches in low permeability materials (e.g.; clays and shales) has failed. Generally this is due to infiltration of rainwater through the cap (NUREG/CR–4918). This infiltrating water causes "water mounding" (the "bathtub effect") within the trenches to a point of trench overflow and surface transport.

The West Valley site has experienced water transport of radionuclides outside the trenches. Because of the low permeability of the soil and the wet climate, water management problems were experienced from the very early years of operations. Despite efforts to address the problem, water accumulated in open, uncompleted trenches and in covered, completed trenches. Water continued to accumulate in several of the original trenches until March 1975, when it crested the original terrain and seeped through the cover of two trenches. That event led to the immediate cessation of disposal operations. Redesigning and reworking of the covers has failed to eliminate the problem of water accumulation in the trenches, thereby preventing permanent stabilization of the disposal area. In its present condition, the closed disposal area will continue to require active maintenance.

Active maintenance is also the plan at Barnwell. After the first four trenches were constructed at Barnwell, a ground water protection system consisting of French drains and sump pumps was installed as a precaution. Barnwell has taken a proactive stance in dealing with ground water contamination, and contamination has not been a problem. The system that Barnwell uses requires management; however, and therefore would not meet the requirement for long–term zero maintenance closure.

The Sheffield site is experiencing lateral ground water transport of radionuclides outside the trenches, but it is still contained within the controlled zone. At least one trench is directly above a sand and gravel lens that is more extensive than previously thought and acts as a rapid migration pathway. An active remediation program (active maintenance) consisting of subsidence, surface water, and vegetation control has kept the radionuclide migration within the site boundary. Without an adequate remediation program, the radionuclide migration could extend beyond institutional control.

Erosion is a geologic/hydrologic process that can be very difficult to predict. In general cases, erosion is greatest early on and stabilizes within 10 years unless extenuating circumstances are at work (e.g., areal uplift, gully headwalling, continued site disturbance, etc.). Erosion at a humid site usually is a problem until vegetation is established. If vegetation control at a humid site is part of the post–closure maintenance activity, erosion may continue to be a chronic problem. Maxey Flats has experienced an facility induced erosional problem of this type with the "east drain" area. An "engineering fix" of spreading 20 mil polyvinylchloride sheets to reduce water infiltration and erosion at the trench site resulted in rapid runoff that accelerated erosion in the "east drain" area. Only West Valley has reported a potential problem with natural erosion of a trench end at this time. All of the streams in the site area are in a state of constant erosion and downcutting. This is probably a result of continental rebound after the last ice age. LaFleur (1979) estimated that downcutting rates of 0.15 to 0.21 cm/yr can be expected to occur in Buttermilk Creek over the next several thousand years. Shifting of the existing channel locations is therefore probable.

To the north of the disposal site lies a gully that drains east to the nearby tributary of Erdman Brook. The head of the gully approaches the site at an angle and separated from it by 30 m (98 ft). An assessment of the gully's advance was made to determine how long it might take for it to move towards, and possibly erode into the disposal site. Assuming that site conditions remain essentially the same as they are at present and have been in recent years, it was calculated that between 580 and 810 years would be needed for the gully to advance 30 m (98 ft) to the disposal site (WVNSC, 1985). Erosion does not therefore present an immediate threat to the disposal site, but implementation of specific erosion control structures and practices at the site would be prudent.

All of the humid LLWDF's have reported problems with trench cap erosion. Erosion caused by external site flooding is remote at Sheffield but internal site flooding caused by high intensity, short–term rain episodes or rapid snowmelts is prevalent. The INEL site experienced two floods caused by rapid snowmelt runoff at the site. Sheffield also experienced a similar situation when a heavy snow fell before the ground was sealed for the winter by freezing. The temperature climbed after the snowfall and the result was a pulse of water not predicted by the standard measure of maximum precipitation records. Subsidence is also a continuing problem at Sheffield and Maxey Flats. Subsidence can be expected at all the sites within fifty years.

Dry sites have their own erosion problems. Initially on a dry site the wind and water will erode until a desert pavement effect has been achieved. Once the desert pavement has been established, further erosion is not likely unless the pavement is disturbed, or in the case of ephemeral streams a sedimentation channel reaches its carrying capacity and a new channel is formed.

Vertical soil movement is also a recurring problem at the sites. Vertical soil movement can be caused by three factors. In the northern sites (Richland, West Valley, Maxey Flats, and Sheffield) where the freeze line penetrates the soil, frost heaving can move large amounts of soil. Solifluction towards void spaces contributes to subsidence problems. A second method of vertical soil movement is soil churning. Soil churning is common in expansive (smectite) clays. Through the wetting and drying cycles expansive clays move soils up and down the soil profile. These expansive clays are of particular interest because they are being considered as a means to enhance the engineering of humid LLWDF sites because of their ability to expand and thereby limit ground water infiltration and/or percolation. Smetite clays are also known for their high cation exchange capacity (CEC). A high CEC will increase the soil's retardation factor for most cations. The third method of vertical soil movement is via animal burrowing. This includes the macroinvertebrates such as earthworms and insects. It is estimated that one ant colony can move 150 kilograms of soil per annum at the Richland LLWDF.

The probability of a seismic event (earthquake) is always a serious design consideration for any constructed facility. Blasting from local construction or mining activity can mimic a seismic event. True seismic events are not predictable, however seismic areas are fairly well defined. Only the Barnwell site is located in a Seismic Zone 3. The seismic zone category is a Universal Building Code (UBC) designation that specifies 0 as no damage and 4 as major damage. The UBC Zone 3 designation corresponds to the modified mercalli index intensity VII or higher and some damage can be expected for most structures. The Maxey Flats, Beatty, and Richland sites are all located in areas (UBC Seismic Zone 2) where an earthquake might occur but would not likely cause much facility damage. It is the contributory effects (e.g., subsidence, liquefaction, elevational changes and mass wasting) of an earthquake that are of interest to the LLWDF. Even a minor earthquake could leave cracks in a clay cap or concrete barriers allowing water infiltration.

A geological event sometimes associated with seismic activity is volcanism. Volcanism should be expected in the subduction zone of the Pacific Northwest, the spreading Columbia rift zone in the west, and over localized hot spots such as the Hawaiian Islands and Yellowstone Park. Only one site, Richland, has been exposed to volcanic activity during operations. Mount St. Helens deposited ash on the site when it erupted in 1980. In the short geologic timeframe of 500 years, volcanism does not appear to be an important siting criterion beyond the realm of common sense.

4.2.4 Anthropogenic Processes and Land Use. Surrounding urbanization and agricultural programs can impact a LLWDF by affecting either surface water or ground water parameters. Overgrazing, paving, or clearcutting of lands outside the LLWDFs boundary can change surface water flow patterns and increase water runoff. These events outside the boundary of the LLWDF might have a negative affect of the performance of the LLWDF.

Increased irrigation can change ground water flow directions, change flow rates, create perched water tables, create subsidence, or lower water tables. The mining of ground water stands out as a long–term (chronic) variable of large areal influence, which will be difficult to predict for the future. Sites with strong population pressures (West Valley and Barnwell) and sites with strong agricultural pressures would be most affected.

Maxey Flats is underlain by the Ohio Black Shale of Devonian age. It has high organic content and the surrounding area could be mined should there be a future need for low–grade organics. Only two sites (Sheffield and West Valley) have a current known mineral resource (coal and oil respective) underlying it. The coal reserves under Sheffield have little current economic value. Current oil and natural gas production at West Valley is limited to secondary recovery from three known fields, the Java 32 km NE, the Fancy Tract 16 km SE, and the Humphrey 32 km SE (DOE, 1986). Mining as an industrial process will probably therefore never be a threat to any of the LLWDF's studied. Resource recovery by individuals (i.e., scrap metal scavengers) however, has been a problem (Beatty). Future scavenging of LLWDF sites will undoubtedly be a problem as the sites are closed and security is relaxed.

5. SUMMARY AND RECOMMENDATIONS

Long–term changes in environmental conditions with the potential for creating a significant impact on LLWDFs have been described in previous sections of this document. Both natural and anthropogenic environmental factors have been considered, and fall into three general categories:

1. Those resulting from changes in land–use pattern
2. Those resulting from changes in climatic conditions
3. Those involving changes in plant or animal community structure, but not related to land–use or climate.

Each of the processes discussed impart their impact in one of two ways:

1. By allowing ground water to infiltrate the waste disposal unit from below
2. By resulting in the loss of the integrity of the cover system so as to allow for either the release of waste to the above–ground environment or the entry of water into the waste disposal units from above.

The purpose of this section is to discuss possible inadequacies inherent to the current 10 CFR 61 regulations, and to offer suggestions as to how these requirements could be modified in order to better evaluate the ability of waste disposal facilities to satisfy their performance objectives.

In order to anticipate the potential impact associated with long–term changes in environmental conditions, regulatory changes should be considered in the following two areas:

1. Site characterization performed during the licensing procedure
2. Operational and post–operational monitoring programs.

5.1 Site Characterization

The site characterization requirements of 10 CFR 61(a)(2) state that "...in choosing a low–level waste site, site characteristics should be considered in terms of the indefinite future and evaluated for at least a 500 year timeframe." In practice, this can be a difficult task, and typically involves the development of long–term predictions that are based on relatively short–term historical data. Basing long–term predictions on short–term data may not be realistic should environmental conditions deviate from historical values. These uncertainties in the predictions required as part of the site characterization process could result in the facility initially meeting the licensing requirements, but not meeting the licensing requirements 100 to 500 years in the future.

In order to better predict site performance over the long term, the site characterization process should be expanded to include the development and analysis of alternative credible scenarios involving substantial deviations from the predictions based on short–term historical data. These scenarios should address the impacts associated with significant variations from predicted land use patterns, climatic conditions, and plant and animal community structure, and the information obtained should be considered in the licensing decisions. While it is unreasonable to assume that all possible long–term scenarios regarding climate, land use pattern, and ecological community structure be identified and evaluated prior to licensing, the site characterization process could do more to address these possible alternate conditions.

Examples of the types of information that should be incorporated into the development of these scenarios are provided below. It should be recognized that whereas the various factors that could be responsible for changes were discussed separately, complex interactions could occur involving almost any combination of factors that might cause a deviation in the expected local or regional environmental conditions.

5.1.1. Land Use. Trends in land use are typically evaluated for the area within a 10 km radius of the facility. To help predict long–term changes, the impacts associated with the following potential factors should be evaluated using questions such as:

- How would large–scale (regional) changes in agricultural or forestry practices impact the water table? Both increases and decreases in agricultural and forestry production should be assessed in terms of their potential impact on the water table.

- How would the development of a major urban area within the watershed in which the disposal facility is located impact the water table? How would the abandonment of a major urban area impact the water table?

- How would the development of surface or subsurface mining within the vicinity of the site impact the performance of a LLWDF? (This should be evaluated even if no recognized minerals or fossil energy sources are known to exist.)

- How would other changes in land use result in a change in the usage of regional ground water?

5.1.2. Climate Change. The site characterization process currently requires a summary of historical data on the meteorology and climate of the area surrounding the site, and assumes that future climatic conditions will remain constant. This information may not be adequate, however, if historical records do not accurately predict significant changes in climatic conditions. In order to help predict impacts on a LLWDF due to long–term changes in climatic conditions, the potential impacts associated with significant changes in temperature, precipitation, and solar radiation should be assessed using questions such as:

- How would the water table respond to a significant increase (or decrease) in temperature, precipitation, or solar radiation? What would be the potential impacts associated with such changes on the performance of a LLWDF?

- How would the plant and animal community structure respond to a significant increase (or decrease) in precipitation? What would be the potential impact associated with such changes on the performance of a LLWDF?

- How would land use pattern be expected to change in response to a significant increase (or decrease) in precipitation?

5.1.3. Changes in Plant and Animal Community Structure. Characterization requirements during the licensing process call for surveys of the plant and animal communities within the area of the disposal site. The assumption is then made that these plant and animal communities will remain constant throughout the lifetime of the disposal facility. The structure of the ecological communities may change significantly, however, over the long term. In order to help predict impacts on the LLWDF due to long–term changes in plant and animal community structure, the potential impacts on a LLWDF should be addressed using questions such as:

- How would significant changes in plant and animal community structure affect the water table?

- How would significant changes in plant and animal community structure alter erosion patterns, thereby affecting the integrity of the cover system?

- What would be the effect of the introduction of exotic deep–rooted plants or burrowing animals on the LLWDF?

5.2 Operational and Post–Operational Monitoring Programs

It is assumed that the post–operational monitoring program will represent an extension of the operational monitoring program, and will continue for a period of 100 years beyond closure of the site. Observation of trends in climatic conditions, land use pattern, and plant and animal populations during this extended period would facilitate the prediction of long–term environmental impacts on the LLWDF. Trends observed in additional, site–specific data from the operational and post–operational monitoring programs may then be incorporated into the appropriate scenarios developed during the site characterization process in order to better project the ability of the facility to satisfy its performance objectives for the duration of the 500 year timeframe associated with the decay to acceptable levels of Class C waste. The need for mitigative actions can be identified more readily using this additional information as well.

In addition to the standard environmental monitoring program currently required by 10 CFR 61, periodic evaluations should be made regarding trends in land use, climatic conditions, and plant and animal population structure. Any apparent impact such changes have on the site should also be identified.

5.2.1 Land Use. Significant changes in regional land use pattern should be identified every decade. Areas dedicated to agriculture, timber production, surface and subsurface mining, etc., should be determined. Trends in the development or abandonment of nearby urban areas should also be noted. Deviations from the land–use patterns predicted during the site characterization process should then be identified, and the potential long–term impacts associated with these changes should be evaluated.

5.2.2 Climate. Regional trends in climatic conditions should be evaluated every decade. Mean (annual and monthly) and extreme (monthly) temperatures should be recorded. Similarly, mean (annual and monthly) precipitation rates should be evaluated. Other climatic factors observed should include the fraction of the total precipitation that falls as snow, the number of frost–free days in the growing season, the depth of frost penetration, and the prevailing wind directions and intensities. Significant deviations in these parameters from what was predicted during the characterization process should be evaluated in terms of their potential impact on the ability of the LLWDF to meet its performance standards.

5.2.3 Plant and Animal Community Structure. Inventories of the flora and fauna found in the vicinity of the site should be conducted every decade. Special emphasis should be placed on the identification of burrowing animals and deep–rooted plant species that have been introduced to the area. Should new species be discovered, their potential impact on the integrity of the waste cover should be evaluated.

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PART II

PERFORMANCE MONITORING TO SUPPORT REGULATORY DECISIONS

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ABSTRACT

Part II of this report contains guidance on the design and implementation of a performance monitoring program for low-level radioactive waste disposal facilities. A monitoring program is described that will assess whether engineered barriers surrounding the waste are effectively isolating the waste and will continue to isolate the waste by remaining structurally stable. Monitoring techniques and instruments are discussed relative to their ability to measure (a) parameters directly related to water movement through engineered barriers, (b) parameters directly related to the structural stability of engineered barriers, and (c) parameters that characterize external or internal conditions that may cause physical changes leading to enhanced water movement or compromises in stability. Data interpretation leading to decisions concerning facility closure is discussed.

FIN No. A6853 — Determination of Information Needed for Performance Modeling of Low-Level Waste Disposal Facilities at Time of Closure

EXECUTIVE SUMMARY

A generic monitoring program was developed for low-level radioactive waste disposal facilities (LLWDFs). Such facilities must contain the waste and minimize radionuclide release as dictated by Federal regulations. Several redundant barriers will be engineered around the waste to satisfy this requirement. Before facility closure, a decision will be made as to whether the engineered barriers are effectively isolating the waste and will continue to isolate the waste by remaining structurally stable. A monitoring program should measure and assess physical changes in the engineered barriers that may eventually allow radionuclides to be released. Monitoring objectives are to assess facility performance by measuring (a) parameters directly related to water movement through engineered barriers, (b) parameters directly related to the structural stability of engineered barriers, and (c) parameters that characterize external or internal conditions that may cause physical changes leading to enhanced water movement or compromises in stability.

Monitoring at LLWDFs should generate data that are scientifically valid and statistically significant. Various factors (e.g., intrusion constraints, monitoring instrument error, and complexities associated with a changing natural environment) will limit the validity and significance of a monitoring program that solely relies upon typical geotechnical and geohydrological tests (e.g., piezometers, tensiometers, and soil/water sampling). The use of intrusive and nonintrusive monitoring techniques and measurements at a representative test area is developed as a viable monitoring strategy.

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PART II

PERFORMANCE MONITORING TO SUPPORT REGULATORY DECISIONS

1. INTRODUCTION

As part of the closure requirements for low-level radioactive waste disposal facilities (LLWDFs), there must be an adequate demonstration that the facility has performed in the manner predicted when the waste disposal license was first issued. Information needed to model and predict facility performance must be gathered before issuance of a license, during facility operation, and at time of facility closure.

Facility performance modeling must exhibit scientific validity and statistical significance and be defensible within the licensing process. Monitoring must be conducted to ensure that the facility performs as planned. The monitoring techniques described in this report provide data to support closure decisions. This report will improve the ability of site operators to plan for LLWDF closure, as well as allow the Nuclear Regulatory Commission (NRC) to make better closure decisions.

1.1 Description of Previous Work

This report describes the fourth and final task in a series designed to determine the information needs for performance modeling of LLWDFs at time of closure. The objective of the program is to identify and develop design criteria and performance standards specific to shallow land burial that will facilitate a confident assessment of the physical status of the facility closure. The intent is to identify the information required to make such an assessment and determine how the required information should be obtained and analyzed.

Task 1 of this work identified engineered and site characteristics that control the performance of LLWDFs. Important engineered and site characteristics were described and summarized in the report generated for Task 1, which culminated in a detailed description of the physical state of a properly functioning LLWDF at the time of closure.

Task 2 identified the information and analyses needed to assess the physical state of LLWDFs. This was accomplished through a workshop attended by ten research scientists held at the Idaho National Engineering Laboratory, August 1-4, 1988. A list of potentially applicable monitoring techniques was identified and systematically considered in relation to (a) the two primary components of the LLWDF (cover system and concrete vault), (b) the primary function of the components (structural stability and hydrological isolation), and (c) a list of potential degradation processes that may impact the performance of these components. The monitoring techniques were then categorized as appropriate to monitor earthen covers, concrete vaults, or both. The information obtained from Tasks 1 and 2 provided some of the basis for this report.

Task 3 involved assessing long-term environmental changes that could act on a LLWDF following the closure. The 100 to 500 year postclosure time frame was used in this task, which represents the time period between the end of the institutional control period (100 years) and the time when the radionuclides contained in Class C wastes have decayed to acceptable levels (500 years). Factors that could result in a change in the stability of the cover system or in a change in the hydrological characteristics of the site were identified and discussed. The factors considered included gross changes in climatic conditions, changes in land use pattern, and changes in plant and animal populations in the vicinity of the site. The results Task 3 are reported in Part 1 of this NUREG/CR report: *Long-Term Environmental Conditions Affecting Low-Level Waste Disposal Site Performance* (White et al., 1990).

1.2 Report Objectives

An important function of LLWDFs is to isolate low-level radioactive waste (LLW) and thus minimize radionuclide release as dictated by Chapter 10, Part 61 of the Code of Federal Regulations (10 CFR 61), "Licensing Requirements for Land Disposal of Radioactive Waste". Although analyses done as part of the Environmental Impact Statement supporting 10 CFR 61 showed shallow land burial to be an acceptable technology, future LLWDFs will most likely employ engineered barriers around the waste. Before closure of a licensed LLWDF, decisions will be made as to whether the engineered barriers are effectively isolating the waste and will continue to isolate the waste by remaining structurally stable. The current state of containment can be measured by monitoring for radionuclide concentrations in the environment surrounding the facility. However, future performance of engineered barriers can not be evaluated by only monitoring for released radionuclides. Monitoring the rate of physical changes can address the likelihood of satisfactory future performance. Satisfactory performance implies that the engineered barriers perform their design function, and thus remain structurally sound, and control water movement through the waste.

The objective of this report is to develop a generic design for a monitoring program to assess physical changes in the engineered barriers of LLWDFs. Various factors (e.g., intrusion constraints, monitoring instrument error, and complexities associated with a changing natural environment) will limit the scientific validity and statistical significance of a monitoring program that solely relies upon standard geotechnical and geohydrological tests (e.g., piezometers, tensiometers, and soil/water sampling). Therefore, alternative and redundant monitoring techniques are necessary to provide data that can facilitate a high quality interpretation of facility performance. To accomplish the report objective, the following tasks are addressed:

- Develop a generic monitoring strategy with defined monitoring objectives.
- Identify changes in the physical state of the facility that indicate active or potential degradation of the engineered barriers.
- Identify and evaluate capabilities and limitations of monitoring instruments and techniques that effectively contribute to monitoring objectives.
- Describe methods to analyze and integrate data to facilitate a scientifically valid and statistically significant interpretation of facility performance.

1.3 Scope

Two documents pertain directly to environmental monitoring and surveillance at proposed LLWDFs (Denham et al., 1988; Sedlet and Wynveen, 1989). Both documents provide valuable guidance and recommendations concerning environmental monitoring to detect released radionuclides. This type of environmental monitoring (detection monitoring) emphasizes measurement of radioactivity or hazardous chemicals in environmental media such as surface water, ground water, soils, air, and biota. These measurements are important and necessary elements of LLW management because they provide a measure of the current performance of a facility. Current performance is evaluated relative to measured radionuclide concentrations above background concentrations. However, monitoring for released radionuclides does not provide the complete information necessary to demonstrate long-term, postclosure performance.

Long-term, postclosure performance depends on changes in the physical state of the facility. Presumably, the facility will be designed and built to isolate LLW. Thus, if the facility is properly constructed, the physical state of the facility must change (such that the original design and/or construction objectives are compromised) for the release of radionuclides to occur. Detection monitoring does not indicate the rates of change in the physical state of the facility, only that a significant change has occurred. Further, detection monitoring does not indicate the cause of a release. Finally, detection monitoring does not allow predictions of future radionuclide concentrations to be made with a known degree of certainty.

Physical monitoring of facility performance acknowledges that degradation of the physical state of the facility can occur before, and result in, the release of radioactivity that can be subsequently measured in the environment. Physical monitoring is based on the principle that it is necessary to do more than just demonstrate current performance; it is also necessary to monitor the rate of change in the physical state of the facility. Further, it is necessary to monitor other characteristics of change (e.g., magnitude and nature) and the environmental processes responsible for the change.

Three sets of characteristics are important to the performance of the engineered barriers:

- Physical
- Chemical
- Hydraulic.

The combination of these three sets of characteristics at any one time is referred to as the physical state of the facility. These characteristics measure the ability of the LLW disposal facility to perform its desired functions. Details of these conditions and the parameters needed to monitor changes in these conditions are provided in Section 3.

Physical characteristics include those that describe the spatial dimensions of the facility and the mechanical processes that may produce changes in physical dimensions. Observable quantities include the dimensions themselves, slope, settlement, and thickness of barriers. Additionally, processes that may produce physical changes can be monitored by observation of, for example, surface erosion.

Chemical characteristics include those that are related to (a) mobility of waste constituents and (b) potential chemical threats to the integrity of engineered barriers, especially those constructed of concrete. Observable quantities that can be monitored to assess changes in the chemical environment include pH, Eh, concentrations of chemical species that may degrade engineered barriers, and concentrations of chemical byproducts of barrier degradation.

Hydraulic characteristics are related to the ability of the facility to control water seepage. Observable quantities include those that (a) describe abundance, distribution, and flow of water and (b) describe the functioning of engineered features as hydrologic barriers.

A complex relationship exists between the measured physical state and true performance of the engineered barriers. Variations and trends in the measured parameters describing the physical state can occur without indicating a change in performance of the barriers. Extraneous factors such as natural variation and monitoring instrument variation must be considered when interpreting the physical state of the facility.

1.4 Time Frame of Consideration

In terms of monitoring, the life of a LLWDF can be divided into four phases: preoperational, operational, short-term postoperational, and long-term postoperational. (NRC, 1987). Figure 1 shows how these monitoring phases correlate with a typical facility development, operation, and closure schedule. NRC may approve shorter or longer time periods if conditions warrant. Preoperational monitoring programs are expected to begin at least 1 year before construction of the facility commences. Once construction and disposal activities begin, the operational phase starts . The operational phase is expected to last 30 years or until active waste disposal ceases. The postoperational phase is divided into two subphases: short-term and long-term. The short-term postoperational phase is expected to last 5 years and includes a site closure and stabilization period and a post-closure observation period. The long-term postoperational phase will last at least 100 years.

In order to develop a data base that will adequately support facility performance evaluations at time of closure, monitoring should be performed throughout the preoperational phase, operational phase, and short-term postoperational phase (Figure 1). Certain elements of a physical monitoring program should continue into the long-term postoperational phase to confirm the closure decision.

Monitoring begins after the site has been characterized, and the monitoring program can adopt the results of an effective, quality-assured, and documented site characterization. Subpart D of 10 CFR 61.50, "Disposal Site Suitability Requirements," requires that a LLW site shall be capable of being characterized, modeled, analyzed, and monitored. NRC (1987, 1988) describe the information needed for site characterization before preoperational monitoring begins. This includes site-specific information on meteorology and climatology, geology and seismology, hydrology, geochemical characteristics, geotechnical characteristics, and biotic features. Parameters and tests for characterizing site for disposal of LLW are addressed in Lutton et al. (1982a, 1982b) and DOE (1988). Recent NRC guidance on the application of

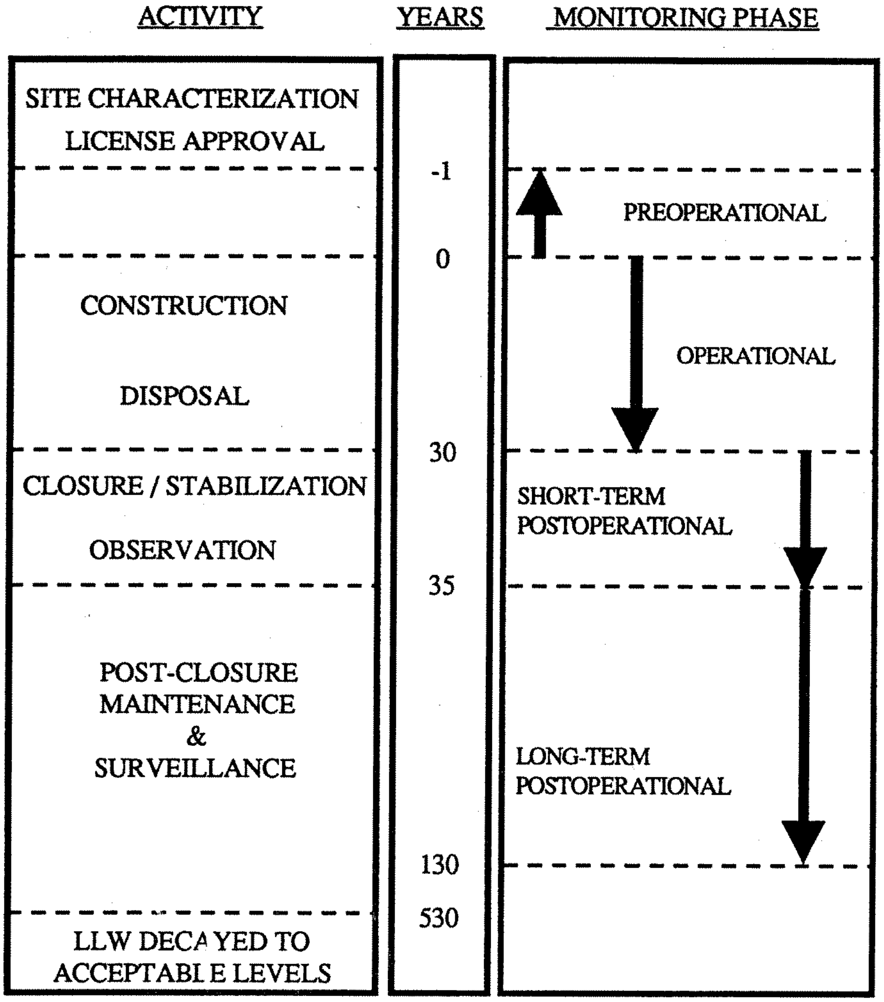

Figure 1. Timing of monitoring phases at LLW disposal sites.

quality assurance for characterizing a LLW disposal site is found in the draft NUREG-1383 (Pittiglio et al., 1989). Some improvements to techniques, methods, and procedures for evaluating hydrology and geochemical characteristics are currently being studied (O'Donnell and Lambert, 1989). But, overall, most of the tests to gather the information needed to characterize a LLW disposal site are documented elsewhere (NRC, 1987 and 1988; Lutton et al., 1982a and 1982b; DOE, 1988) and will not be addressed here.

1.5 Summary of Pertinent Federal Regulations

Most of the Federal regulations of concern to this program are contained in 10 CFR 61: "Licensing Requirements for Land Disposal of Radioactive Waste." Part 61 applies primarily to near-surface disposal facilities, although provisions are made for the implementation of additional regulations for alternative disposal technologies, should such technologies become available. Several such technologies have been described by others (Kane and Tokar, 1987).

Performance objectives for the disposal of LLW in near-surface disposal facilities are established in subpart C of Part 61. In effect, the monitoring program recommended in this task will be designed with the purpose of satisfying these performance objectives. The performance objectives of subpart C include the following:

- Protection of the general population from the release of radioactivity. Concentrations of radioactive materials that may be released to the general environment in ground water, surface water, air, soil, plants, or animals must not result in an annual dose exceeding an equivalent of 25 mrem to the whole body, 75 mrem to the thyroid, and 25 mrem to any other organ. Reasonable effort should be made to maintain releases of radioactivity in effluents to the general environment as low as is reasonably achievable [10 CFR 61.41].

- Protection of individuals from inadvertent intrusion. Design, operation, and closure of the land disposal facility must ensure protection of any individual inadvertently intruding into the disposal site and occupying the site or contacting the waste at any time after institutional controls over the disposal site are removed [10 CFR 61.42].

- Assurance of site stability following closure. The disposal facility must be sited, designed, used, operated, and closed to achieve long-term stability of the disposal site and to eliminate to the extent practicable the need for ongoing active maintenance of the disposal site following closure so that only surveillance, monitoring, or minor custodial care are required [10 CFR 61.46].

This final objective of ensuring stability of the site is of primary importance to this program. Protection of the general population from releases of radioactivity will be accomplished primarily through ensuring the stability of the site. As stated in the regulations, the key to meeting these performance objectives is the stability of the waste disposal system. Once the waste is emplaced, the potential for water coming in contact with the waste must be minimized. By maintaining the stability of the site following closure, long-term active maintenance of the site can be avoided, potential exposures to intruders can be reduced, and migration of radionuclides can be minimized [10 CFR 61.7(b)(2)].

Subpart B of 10 CFR 61 describes the licensing requirements of a commercial LLWDF. A major part of this licensing process is the submission by the applicant of site-specific technical information needed to demonstrate that the performance objectives and technical requirements can be met. Among the types of technical information required are detailed descriptions of a variety of environmental features of the site. These include

- Meteorologic, climatologic, and biotic features of the disposal site and vicinity [10 CFR 61.12(a)].

- Design features related to infiltration of water; integrity of covers for disposal units; structural stability of backfill, wastes, and covers; contact of wastes with standing water; and disposal site drainage [10 CFR 61.12(b)].

- Principal design criteria and their relationship to the performance objectives [10 CFR 61.12(c)].

- Design basis natural events or phenomena and their relationship to the principal design criteria [10 CFR 61.12(d)].

- Environmental monitoring program to provide data to evaluate potential health and environmental impacts, and the plan for taking corrective measures if migration of radionuclides is indicated [10 CFR 61.12(l)].

A number of technical analyses are also required by subpart B of 10 CFR 61 as part of the licensing process that relate to this work. These include

- Pathway analyses to demonstrate protection of the general population from releases of radionuclides. Pathways to be analyzed include air, soil, ground water, surface water, plant uptake, and exhumation by the activities of burrowing animals [10 CFR 61.13(a)].

- Analyses of long-term stability of the site and the associated need for ongoing active maintenance after closure. This must be based on analyses of active natural processes such as erosion, mass wasting, slope failure, settlement of wastes and backfill, infiltration through covers over disposal areas and adjacent soils, and surface drainage of the disposal site. The purpose of these analyses is to provide reasonable assurance that there will not be a need for ongoing active maintenance of the disposal site following institutional closure [10 CFR 61.13(d)].

Finally, the technical requirements for land disposal facilities provided in subpart D of 10 CFR 61 have some sections that pertain to this project. These include

- The disposal site shall be capable of being characterized, modeled, analyzed, and monitored [10 CFR 61.50(a)(2)].
- Site design features must be directed toward long-term isolation and avoidance of the need for continuing active maintenance after site closure [10 CFR 61.51(a)(1)].
- Covers must be designed to minimize water infiltration to the extent practicable, to direct percolating or surface water away from the disposed waste, and to resist degradation by surface geologic processes and biotic activity [10 CFR 61.51(a)(4)].
- The disposal site must be designed to minimize the contact of water with waste during storage, the contact of standing water with waste during during disposal, and the contact of percolating or standing water with waste after disposal [10 CFR 61.51(a)(6)].
- At the time a license application is submitted, the applicant shall have conducted a preoperational monitoring program to provide basic environmental data on the disposal site characteristics [10 CFR 61.53(a)].
- During the land disposal facility construction and operation, the licensee shall maintain a monitoring program capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary [10 CFR 61.53(c)].
- After the disposal site is closed, the licensee responsible for postoperational surveillance of the disposal site shall maintain a monitoring system based on the operating history and the closure and stabilization of the disposal site. The monitoring system must be capable of providing early warning of releases of radionuclides from the disposal site before they leave the site boundary [10 CFR 61.53(d)].

1.6 Document Organization

Section 2 develops the monitoring objectives and strategy. Monitoring at LLWDFs is divided into four phases: preoperational, operational, short-term postoperational, and long-term postoperational. Section 2 also includes conceptual models and a brief discussion of the importance of quality data to decisions on facility closure.

Section 3 of this document provides an overview of the parameters that can be applied toward monitoring the performance of a LLWDF. These parameters are divided into three general groups: water movement, the stability of the facility, and degradation mechanisms.

In Section 4, the various techniques and instrumentation that could be used to measure the parameters identified in Section 3 are described. These descriptions include the rationale for using each technique, factors pertaining to the location, implementation and sampling or measurement frequency of the technique, the equipment required to perform the measurements, and considerations pertinent to the interpretation of data.

Section 5 outlines the the potential application of a representative test area to provide information to supplement the monitoring program, as described in Section 4. This discussion includes a description of the generic design and required features for the representative test area and its purpose and limitations.

The analytical approach to the overall performance monitoring system is described in Section 6. This includes a description of the statistical considerations of the monitoring program and an interpretation of the potential uses of the data acquired in the monitoring data.

Section 7 contains a summary of the document in the form of an implementation plan and the conclusions reached during this report.

2. MONITORING OBJECTIVES AND APPROACH

2.1 Conceptual LLWDF Models

To provide a focus for the evaluation of physical monitoring techniques, some assumptions must be made concerning the type of disposal facility to be monitored. The "new-generation" conceptual LLWDF considered in this report is a near-surface concrete vault with an engineered cover. These two features are common to most engineered alternatives to shallow land burial. Further, NRC is emphasizing a cover and vault system when developing technical information (O'Donnell and Lambert, 1989; Sedlet and Wynveen, 1989).

The terminology used in this document to identify engineered barriers that comprise the cover and vault is defined below and shown in Figure 2. The LLWDF has engineered barriers termed here as

- Vegetative soil cover
- Cobble/boulder bio-barrier
- Sand/gravel layer
- Clay low-permeability layer
- Sand/gravel drainage backfill surrounding vault.

The cover is designed to reduce water infiltration, erosion, and biotic intrusion. The vault is a stabilized enclosure constructed of reinforced concrete that provides resistance to subsidence or collapse. The movement of solutes (including released radionuclides) through concrete will be primarily by diffusion as long as the barriers remain structurally intact (Clifton and Knab, 1989).

LLW, located inside high-integrity containers, is surrounded by fill material (sand, gravel, concrete, grout) placed in the interstices between the waste containers. The high-integrity container (HIC) is a modular waste receptacle designed to provide greater structural stability and resistance to water movement than a standard drum or wooden box. The fill may provide some structural stability and resistance to water movement. Figure 2 shows these engineered barriers as a conceptual model of a LLWDF.

The described engineered barriers are reasonable examples of barrier types, and many other alternative designs are possible. However, these barriers adequately represent the cover and vault in terms of monitoring considerations.

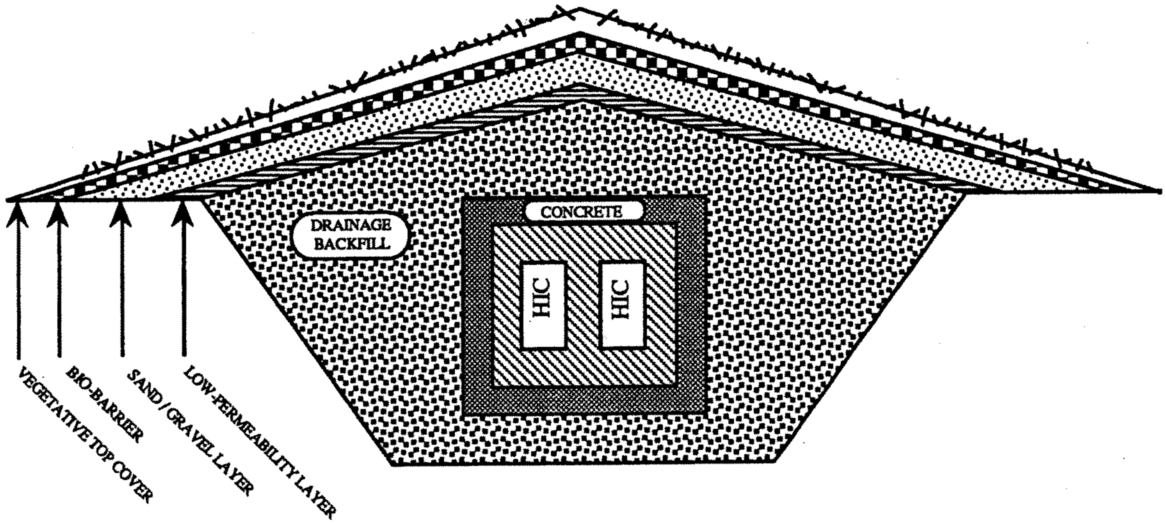

Figure 2. Conceptual model of a LLWDF.

Environmental processes influence the engineered barriers' ability to isolate LLW from the environment and impart a potentially changing environment to the engineered barriers. Six types of environmental processes will affect the disposal facility:

- Mechanical (seismic activity, gravity and wind)
- Hydrologic (rain, snow, flood, and ground water)
- Meteorological (effects of weather conditions such as freeze/thaw cycles, vegetation denudation, and evapotranspiration)
- Biological (activities from animals, plants, and microbes)
- Chemical (those controlled by chemical thermodynamics laws such as precipitation, dissolution, and oxidation)
- Human (facility construction and operation, monitoring activities, and intrusion by monitoring instrumentation).

Each barrier will be subjected to certain environmental processes. The potential of a certain process acting upon a barrier will depend on both the geographic setting and the arrangement of barriers. Each barrier interacts directly with only one or two adjacent barriers. The vegetative top cover is directly impacted by above ground environmental processes. Other environmental processes may originate below ground or from within a barrier. Assuming the upper barriers are well designed and do not completely fail, a lower barrier will be buffered from many environmental forces. For example, as long as the biobarrier remains intact, the concrete is protected from biointrusion. Consequently, each barrier need only be monitored for damage from certain environmental forces.

Two general types of settings represent the range of environmental conditions found in the continental United States: (1) an arid environment typical of western states and (2) a humid environment typical of eastern states. Precedence for classifying these two extreme environments is found in Sedlet and Wynveen (1989) and Rogers and Associates Engineering Corporation (1987).

The arid, western site is characterized by warm summers marked by very low effective precipitation (precipitation < potential evapotranspiration) resulting in soil moisture deficiencies. Winters are characteristically cold with occasional heavy snowfall. High winds often cause blowing soil. Additional characteristics include low annual precipitation (<20 cm) and 60 - 100 m depth to water table.

The humid, eastern site is characterized by a continental climate. Summers are characterized by rain, hot temperatures, and high humidity and winters by cold temperatures and occasional snowfall in the north or by moderate temperatures and long rainy seasons in the south. Additional characteristics include high annual precipitation (>100 cm) and 10 to 15 m depth to ground water table.

2.2 Factors Controlling LLWDF Performance

LLWDF performance is directly associated with the physical state of the facility (Cerven and Otis, 1987). The three primary factors controlling performance are derived from the following fundamental principles:

- The contact of water with LLW, both during operation and after the site is closed, should be minimized. Water is the primary vehicle for waste transport, and its contact with waste can contribute to accelerated degradation of the engineered barriers surrounding the waste.
- Stability of the engineered barriers surrounding the waste should be maximized. Stability serves to reduce subsidence or heaving, eliminate need for facility repair, maintain integrity of barriers to prevent inadvertent intrusion, and maintain ability of barriers to control water seepage through waste vault.
- External factors could result in changes in the stability of the engineered barriers and/or in changes in the hydrological characteristics of the site. The long-term impacts associated with external environmental conditions are addressed in the report prepared for Task 3 of this work (White et al., 1990).

2.3 Objectives of Performance Monitoring Program

The ability of a LLWDF to isolate waste from the surrounding environment depends on the performance of the barriers engineered around the waste. Monitoring objectives are derived from the factors controlling facility performance as identified above.

The first monitoring objective is to quantify conditions directly related to infiltration into and seepage through the engineered barriers by measuring pertinent hydrologic parameters. Interpretation of such monitoring parameters should result in describing the spatial and temporal variation of water movement through the engineered system. A properly functioning engineered barrier system should result in a specified desirable seepage pattern (in general, divert precipitation recharge away from waste). Deviations from this ideal flow pattern could compromise waste isolation.

The second monitoring objective is quantify conditions directly related to the stability of the facility. There are two approaches to monitoring stability. The first is to determine stresses (or pressure) acting on points within the engineered barriers. Both pore water pressure and total stress should be measured to estimate effective stress. The second approach is to monitor changes in the magnitude of deflections or displacements of certain barrier components. Interpretation of such variables should result in an understanding of the structural stability of the facility. Projections of stability trends will be considered in closure decisions.

The third monitoring objective is to characterize the conditions that control changes in the physical state of the barriers. This includes characterization of physical changes that may allow increased water movement through the waste and changes that signal impending structural compromises. Characterization includes type, magnitude, and rate of physical changes as well as identification of the degradation mechanism that is probably responsible for the change.

In summary, the monitoring program should

- Provide data to assess the facility's current ability to isolate and stabilize waste.
- Provide data needed for performance modeling to support a conclusion that the facility will continue to isolate and stabilize waste.
- Provide information about the location and cause of enhanced seepage rates and structural defects.
- Not compromise the facility's ability to isolate waste by intrusion. The monitoring equipment implementation and data collection activities must not compromise performance by their intrusion through the barriers.
- Provide high quality assurance levels with redundant physical data. A component approach should be employed to provide redundant physical data by integrating several types of field measurements to assess each physical parameter. Use of redundant measurements should help ensure that quality assured data are available and provide some level of confidence to the data assessment.
- Be adaptive to modifications. For example, as new data collection, processing, and interpretation techniques develop, the program should be capable of modification to benefit from these developments.

2.3.1 Preoperational Performance Monitoring Activities. Before operation of the LLWDF, site-specific information must be collected as a basis for long-term data analysis. Data collected may be used to predict how the facility will behave during operational and postoperational phases. These data should include

- Geotechnical parameters: swelling index, compression index, preconsolidation pressure, and in situ effective stress
- Soil strength parameters and hydraulic properties
- Meteorological data and ground water levels over several seasons.

2.3.2 Operational Performance Monitoring Activities. The monitoring tasks to perform during facility construction and waste disposal are

- To verify that the engineered structure behaves in the anticipated manner according to the design basis
- To establish control for the placement of wastes to avoid differential settlement or long-term large settlements of the structure
- To provide quality assurance for the materials and construction methods used to build engineered barriers.

2.3.3 Short-term Postoperational Performance Monitoring Activities. Plans for postoperational monitoring should be based upon information obtained during previous phases. Monitoring during the short-term postoperational phase should satisfy two primary tasks:

- To ensure quality control of the placement of final cover and the establishment of the vegetative layer
- To interpret conditions to make decisions that permit or deny closure license.

2.3.4 Long-term Postoperational Performance Monitoring Activities. Long-term postoperational monitoring will be based on information gained during the earlier portions of the monitoring program and should represent a subsection of the short-term postoperational monitoring program. Selection of techniques that should continue to be employed depends on site characteristics, facility design features, performance of the monitoring technique, and the degree to which facility performance is understood. The postoperational program should be designed to ensure that the site continues to meet the closure requirements. Most of the environmental sampling will be terminated by the beginning of the long-term postoperational phase, which should include the following (Shum et al., 1989):

- Periodic physical surveillance to identify needed repairs.
- Ground water sampling. This portion of the sampling program should be continued during the postoperational phase to provide data on the long-term impact of the site. If no potential problems are identified, the ground water monitoring can gradually be reduced.
- Vegetation, particularly deep-rooted plants, should be sampled periodically for the uptake of radioactivity.
- Burrowing animals or their fecal matter should be sampled periodically and analyzed for radionuclide concentration.

2.4 Monitoring Strategy

Data associated with three types of parameters should be collected to fulfill monitoring objectives:

- Parameters directly related to seepage through engineered barriers
- Parameters directly related to the engineered barriers' structural stability
- Parameters characterizing external or internal conditions that may cause physical changes leading to enhanced water movement or compromises in stability.

A monitoring program that requires substantial access through the engineered barriers is likely to compromise the design function of the barriers. However, all engineered barriers of a LLWDF should be evaluated. Environmental processes can change the physical state of each barrier, and these changes will likely result in spatial variability within each barrier. One approach to evaluate variability is to attempt to measure certain important conditions (such as pore water pressure, water content, and hydraulic conductivity) throughout the facility. This implies a level of instrumentation density that could adversely affect the engineered barriers. An alternative approach is to quantify the variability throughout the facility by limited intrusive measurements and to monitor spatial changes by remote (and nonintrusive) measurements. Then, a detailed performance assessment could be conducted at a nearby testing area. The combined use of (a) intrusive measurements, (b) nonintrusive measurements, and (c) measurements at a representative test area is the approach taken in this study.

Intrusive measurements are predominantly location-specific measurements obtained using in situ instruments and soil, pore water, and pore gas sampling. Intrusive measurements are most representative of the area immediately surrounding instrument, sample, or observation. Intrusive measurements can provide relatively accurate and unique, yet localized, data as compared to reasonable measurement alternatives.

Nonintrusive measurements using certain geophysical, remote sensing, and photogrammetric techniques do not require any intrusion into sensitive areas of a LLWDF. Nonintrusive measurements are most representative of bulk conditions, and therefore, resolution of actual conditions at specific locations is a major issue. Information provided by nonintrusive measurements is sometimes only qualitative. Nonintrusive measurements can assess spatial variability between local intrusive measurements and observe large-scale changes that are masked using only intrusive measurements. Valid local measurements must be available to interpret the concurrent responses recorded by nonintrusive measurement techniques.

Measurements at a representative test area provide information about the disposal facility that cannot be otherwise obtained because of adverse impacts from monitoring equipment or activities. A representative test area involves features such as

- Scaled-down surrogate vault with nonhazardous materials inside and an overlying surrogate engineered cover

- Access trench with replaceable monitoring instruments and nondestructive testing

- Archival disposal unit with retrievable coupons (small removable samples) of concrete and container materials

- Undisturbed region not directly impacted by engineered facility or disposal activities (representative of natural or background conditions).

Difficulties in defining the relationship between the test area and the actual disposal facility are expected; however, use of proper statistical methods can alleviate many of the important problems.

The integration of representative test area data with data obtained at the actual facility (using intrusive and nonintrusive measurements) can be statistically viewed as three data populations or monitoring regions: (1) actual facility, (2) surrogate facility with associated access and archival disposal unit, and (3) undisturbed region not directly impacted by the engineered facility or disposal activities. Establishing relationships between these three regions (data populations) is needed to resolve true physical changes within the actual facility.

Each of the three regions is monitored for unique purposes as part of the overall monitoring objectives. The purpose of monitoring at the actual facility is to assess actual changes in the facility. The purpose of monitoring the surrogate facility is to evaluate barriers that are unaccessible at the actual facility. Further, instrumentation and monitoring tests themselves can be evaluated as to failure rate and measurement accuracy. The purpose of monitoring the undisturbed region is to assess the changing baseline conditions (not impacted by disposal activities) Also, baseline monitoring can quantify the natural physical changes not associated with disposal activities but which could occur in the actual facility. The combination of the three data populations can remove most extraneous sources of measurement variation from the true physical changes that signal a change in performance.

2.5 Interpretive Considerations

Parameters recommended for performance monitoring of LLWDFs reflect a wide range of data types, from simple observations to highly controlled measurements taken with sophisticated instrumentation. Specific monitoring techniques and instruments discussed in this report illustrate these various data types and describe an array of related variables, such as frequency and duration of measurements and spatial and temporal factors, which strongly influence how these data may be interpreted. Interpretation and use of data link the monitoring program to the overall objectives of a project. The subject of this report is to recommend methods for the collection of monitoring data that will provide high quality information to support regulatory decisions on LLWDF closures. The quality of decisions rendered is highly dependent on the quality of data used in the decision making process. Therefore, a thorough understanding of the various levels of quality corresponding to data generated in the monitoring program and factors affecting their quality is essential to making well informed decisions.

The quality level of data is determined by several factors. The degree of measurement subjectivity and the reproducibility of individual measurements are basic characteristics of data that the user should be keenly aware of before decisions based on monitoring data are made. Conventionally, these quality characteristics are referred to as accuracy, precision, completeness, comparability, and representativeness (EPA, 1989). Given ideal circumstances where all outside influences are under the control of the scientist or engineer, the highest levels of data quality should be achieved. However, the influences of natural variability, instrument variability, human error, and chance preclude ideal conditions in the real world. Consequently, it is imperative to understand the limitations of monitoring efforts in terms of sources of error that may be encountered. Equally important is an understanding of the use specific types of data may serve and related limitations. These considerations should be addressed during the initial design of a LLWDF to ensure that the monitoring program's data collection and interpretation procedures meet the needs of facility closure decision makers.

3. IDENTIFICATION OF PHYSICAL MONITORING PARAMETERS

3.1 Direct Indicators of Water Movement

Given that the earthen cover and concrete will behave as porous media, hydrologic models of water flow through porous media must be used to assess performance. Data are needed to input to any chosen hydrologic model. Several mathematical models and concepts are provided below to explain the relationship between important parameters and illustrate a fundamental use of these parameters.

Fluid flow through porous media is typically described quantitatively using Darcy's Law (Freeze and Cherry, 1979):

$$q_i = -K_i \frac{dh}{dx_i} \qquad (1)$$

where q_i is the flux of water in the x_i direction; K_i is the hydraulic conductivity of the media in that direction; and dh/dx_i is the hydraulic gradient in that direction. The total hydraulic head, h, can be written as the sum of the pressure head (Ψ) and the elevation head (z). Note that the pressure head has negative values (tension or suction) for unsaturated conditions. For any unsaturated media, there is a close relationship between the soil water content (θ) and the pressure head as shown in Figure 3(a). In the unsaturated form of Darcy's Law, the hydraulic conductivity is considered to be a nonlinear function of water content or pressure head. Figure 3(b) shows typical unsaturated hydraulic conductivity curves for sandy and clayey soils as a function of pressure head. [Hydraulic conductivity versus water content can be derived from curves 3(a) and 3(b).]

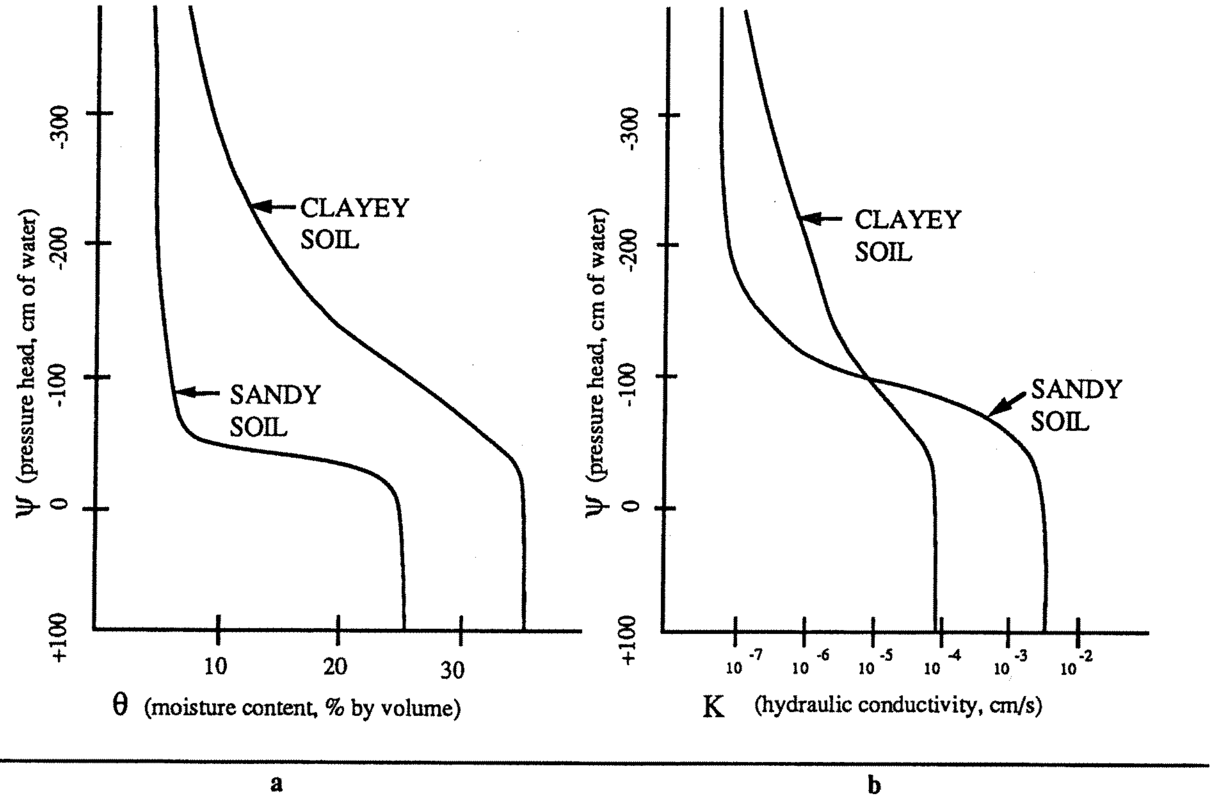

Figure 3. Typical curves for relationships between porous media hydraulic properties. Part **a** presents water content versus pressure head curves for two representative soils. Part **b** presents hydraulic conductivity versus pressure head for two representative soils.

Healy (1989) examined four methods to estimate seepage through a LLWDF cover in Sheffield, Illinois. Sheffield (precipitation of 90 cm/yr) may represent a setting with conditions between the illustrative humid and arid conditions (Healy et al., 1986). Healy (1989) concluded that the Darcy and surface-based water-budget methods were the least constrained by limitations and are the preferred methods. The Darcy method has the advantage of being able to distinguish seepage occurring at different locations.

The surface-based water-budget equation can be written as

$$D = P - R - ET - \Delta S \tag{2}$$

where D is seepage through the vegetative top cover; R is surface runoff; ET is evapotranspiration; and ΔS is change in soil moisture stored within the vegetative top cover. All terms have units of length per time. Seepage through the vegetative top cover is not expected to equal seepage through vault or drainage backfill. Engineered alternatives to shallow land burial burial will likely employ some sort of seepage diversion barrier above the vault (Schultz et al., 1988). Ideally, most water seeping through the vegetative top cover will be diverted around backfill immediately surrounding vault.

Thus, to be able to quantify parameters relating to seepage through the engineered barriers of a disposal facility, it is necessary to characterize and/or quantify four characteristics relating to unsaturated and saturated flow. These characteristics are (a) energy levels or hydraulic head; (b) water content; (c) relationships between hydraulic conductivity, moisture content, and pressure head; and (d) recharge conditions. These four general seepage characteristics are shown in Table 1.

Table 1. Seepage characteristics and parameters that could be monitored after facility is constructed

Seepage Characteristics	Measurable Parameters
Hydraulic head distribution	Pressure head (unsaturated and saturated) Pore vapor relative humidity Electrical resistance[a] Heat dissipation[a]
Water content distribution	Gravimetric analysis of samples Electrical resistance Heat dissipation Dielectric constants Neutron thermalization Gamma ray attenuation
Hydraulic properties	Hydraulic conductivity as function of water content[b] Hydraulic conductivity as function of pressure head[b] Water content as function of pressure head[b]
Recharge conditions	Precipitation Runoff Water in ponds Water in drainage system Evapotranspiration Soil moisture storage Infiltrability Movement of water transported tracer

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a. Depends on relationship between water content and pressure head

b. Measured primarily during site characterization. Relationships will be estimated after facility is constructed.

The desired hydrologic properties of each barrier depend on the component's desired function. For example, sand/gravel layers should have high permeability and promote water movement either downward towards drainage collection systems or laterally away from the concrete vault. Hydraulic barriers such as clay layers should have low permeabilities. Geosynthetics should be void of holes and seam openings. Concrete should have a low-permeability (even when saturated) and be void of cracks or other fouling. As previously discussed, many arrangements of engineered barriers are possible given the site's hydrologic regime. One significant difference is whether the water is expected to be diverted by a hydraulic barrier (clay layer) or by a capillary barrier (sand/gravel layer) or both. The component's desired function should be considered when assessing acceptable hydraulic behavior.

Because clay and concrete have very small pores, these materials may become saturated because of capillary phenomena drawing and retaining available water from adjacent larger-pored materials. In humid environments, clay and concrete may remain saturated. When materials are continually saturated, the facility should keep the rate of seepage from leaving the saturated materials very low. In this case, capillary phenomenon require that large hydraulic head gradients and near zero pressure heads exist to empty the relatively small pores into the larger pores.

3.2 Direct Indicators of Stability

Performance of the LLWDF is affected by the stability of engineered barriers. In association with LLWDFs, stability may be defined as the physical condition of the structure that enables it to perform as intended. Compromises in stability could include the following:

- Cracks, significant erosion, or shear failure of the engineered cover
- Differential settlement that produces free fluid transport through cracks in the concrete
- Large settlements that alter drainage and the integrity of the engineered cover
- Significant deterioration of the concrete that causes cracks in zones of reduced strength
- Upheaval of the base slab from changes in the substructure stress states, moisture conditions, and expansive soils. (This may be of particular importance during the operational phase.)

Stability is a function of several factors. These include compatibility of the initial site conditions with the engineered structure, quality control for materials used and construction methods, and deterioration of the structure over time.

Proper selection of the initial site will reduce site/structure compatibility problems. However, other factors may predetermine the location of the site. Monitoring of conditions before design and construction identifies potential problems such as fluctuations in the ground water level or expansive soils. Preventative measures such as soil stabilization, soil replacement, or adjustments to the design may be made to ensure long-term stability of the LLWDF.

Quality controls during the construction and operational phases of the LLWDF are necessary to eliminate unexpected releases during the long-term monitoring phase. Materials such as concrete, steel, soil, or geosynthetics will be inspected before and during installation. Each step during construction of the LLWDF will be inspected to evaluate long-term stability.

Deterioration of the structure over time is difficult to predict. The limited data available should be used in the design to account for eventual reductions in stability. Appropriate factors of safety will also promote long-term stability for the LLWDF.

Measurable parameters that determine stability of the LLWDF may be divided into two categories. The first are those used to calculate effective stress within earth materials. The second are direct measurements for relative displacements of the LLWDF components.

Effective stress is the load per unit area (total stress) acting on a soil surface minus the pore water pressure, as shown below (Lambe and Whitman, 1969).

$$\sigma' = \sigma - u \qquad (3)$$

where, σ' is effective stress, σ is load per unit area, and u is pore water pressure. Effective stress produces frictional resistance in soils and rocks and is therefore directly proportional to the shear strength (Das, 1984). Calculations for settlement and slope stability are based on effective stress.

Direct measurement of displacements within the LLWDF may be used to monitor several indicators of performance. These include slope stability and creep, uplift or gross settlement of the structure, differential settlement, loss of concrete integrity over time, and tilt of the vault.

Data required for stability evaluation may include the following:

- Pore water pressure at selected locations within the cover, within the slopes adjacent to the drainage backfill, and at the base of the backfill
- Total stress below the entire structure
- Measurement of displacements using a variety of instruments at several locations within the LLWDF including around the concrete barriers and within the cover
- Direct readings from strain gages built into the concrete walls or base slab.

Pore water pressure measurements are critical to certain aspects of the long-term monitoring program. For structural stability assessment, these measurements may be used to determine the effective stress at certain locations within the LLWDF. If the pore water pressures exceed threshold levels at these locations, effective stress may be reduced to where a failure could result. Modes of slope failure possible for the conceptual model are as follows:

- Eventual clogging of the drainage layer in the cover may occur. This could result from intrusion through the biobarrier by fine soil or the growth of biofilms within the drainage layer. Water infiltrating may reach the low-permeability interface. The increase in pore water pressure would reduce the effective stress and, therefore, shear friction. The combination of reduced shear friction and increased overburden (from the water present) could lead to a planar failure of the cover at the interface.
- Removal of water through the drainage system surrounding the vault creates a hydraulic gradient with respect to outside the low permeability layer. Any loss in integrity of the clay layer will cause seepage from outside to the inside. Fine materials could be transported into the drainage material and create a void in the slope area. Depending on the magnitude of pore water pressures allowed to develop, local shear failure of the slope outside the drainage backfill may occur. Possible consequences of this event may include localized subsidence of the cover surface and/or changes in the drainage characteristics of the cover or backfill.

Total stress measurements taken below the entire structure may be used to identify changes in the uplift forces acting on the vault. An increase in total stress will accompany upward movement of the vault and would likely correspond to the presence of water build-up within the backfill surrounding vault. The utility of taking total stress measurements in this case is questionable, because direct measurements of uplift could be made by surveying.

During the operational phase of the LLWDF, total stress measurements taken beneath the vault could be very useful. Taken in conjunction with pore water pressure measurements, these data could be used to predict settlement as the load (waste material) is placed within the vault. Conditions leading to differential settlement could be anticipated and avoided.

Displacements may be measured by direct surveying, slope indicators, and strain gages. Surveying will provide data on the settlements that actually occur in the LLWDF. Slope indicators may be used to measure creep of the cover materials, changes in the slopes adjacent of the drainage backfill, or tilt of the vault walls. Strain gages directly measure deformations of the vault walls or base slab.

3.3 Parameters Related to Degradation Mechanisms

As discussed previously, continuous processes (such as erosion and chemical attack) can act as degradation mechanisms and cause damage to the engineered barriers. For purposes of this report, damage and degradation are defined to include (a) physical changes that influence seepage characteristics by altering the barriers' hydraulic properties or increasing recharge and (b) physical changes that alter the stability of individual engineered barriers The objective is to monitor the rate that damage is accumulating. Further, certain types of damage can be attributed to specific degradation mechanisms. If the causes of degradation were known, then perhaps corrective measures could be taken. A secondary monitoring objective is to identify which mechanism is responsible for the damage.

Physical and chemical parameters can be identified that characterize the changes (damage) and/or identify the responsible degradation mechanism. It is helpful to categorize these changes by potentially responsible degradation mechanism(s). It is helpful to distinguish which mechanisms could potentially affect each engineered component, assuming that adjacent components have not totally failed.

Often it may be practically impossible to monitor specific impacts of degradation mechanisms and/or identify the specific mechanism that is responsible. In these cases, enhanced water seepage warns of damage because of nonspecific mechanisms. Water seepage alone often leads to enhanced seepage rates, and the effects of many of component-specific degradation mechanisms are magnified because of water seepage. This is caused by three factors

1. Hydraulic conductivity increases with increasing water content as indicated by the relationship between hydraulic conductivity and water content (Figure 3, Section 3.1).
2. Preferential flow phenomenon causes seepage rates to increase more rapidly once water establishes a flow path.
3. Continuous water movement causes nonsteady state conditions for chemical reactions, and higher dissolution, precipitation, and leaching rates are likely.

In conclusion, enhanced water seepage should be considered as a degradation mechanism for all of the engineered components.

Tables 2, 3, 4, 5, and 6 list degradation mechanisms that could potentially compromise the performance of an engineered barrier. Brief definitions of each mechanism are given. Parameters are listed that can be measured to determine the damage of a particular mechanism. If possible, parameters are identified that could distinguish a particular mechanism as the cause of damage. Details concerning the relationships between degradation mechanisms and monitoring parameters are provided in Section 4.

Table 2. Degradation mechanisms and parameters to consider for geotextiles or geomembranes (Richardson and Koerner, 1987)

Mechanism	Definition	Measurable Parameters
Chemical attack	Many waterborne chemicals react with thermoplastic materials resulting in geosynthetic deterioration	Geosynthetic fouling Byproducts of polymer reactions
Photo-chemical attack	Oxidation of polymers by ultraviolet light	Geosynthetic fouling
Ozone attack	Oxidation by Ozone	Geosynthetic fouling
Biological intrusion	Animal or plant intrusion into the geosynthetic	Intrusion depth Holes in geosynthetic
Differential settlement	Mechanical settling from changing weight and compaction of host materials, waste, vault, and cover	Holes, tears, and depression
Thermal effects	Stretching and shrinking caused by temperature changes	Holes, tears, and depression

Table 3. Degradation mechanisms and parameters to consider for a concrete vault (Loadsman et al., 1988; Clifton and Knab, 1989)

Mechanism	Definition	Measurable Parameters
Differential settlement	Mechanical settling from changing weight and compaction of host materials, waste, vault, and cover	Change in cover elevation Concrete barrier continuity and thickness Gaps at joints Cracking within barrier
Cracking	Cracking caused by stress, shrinkage, thermal changes, and other miscellaneous factors	Concrete fouling Concrete density Crack size and nature
Reinforcement corrosion and chloride attack	Steel corrosion by waterborne chloride ions and subsequent concrete cracking	Concrete fouling Aqueous iron and chloride concentration
Sulfate attack	Waterborne sulfate ions and complexes react with cement paste constituents causing concrete to expand and deteriorate	Concrete expansion and fouling Aqueous sulfate concentration Eh and pH at concrete surface
Acid attack	Concrete degradation by acidic water	Concrete fouling pH at concrete surface
$Ca(OH)_2$ leaching	Cement constituents leached from concrete by percolating water	Concrete fouling Aqueous calcium concentration pH at concrete surface
Microbial attack	Oxidation and biodegradation of coatings and sealants	Concrete fouling Eh and pH concrete surface Indicators of metabolic activity
Alkali-aggregate reaction	Internal reactions between cement paste constituents and siliceous components in concrete aggregate	Concrete expansion and fouling
Carbonation	Carbon dioxide reactions with cement paste constituents	Concrete shrinkage and fouling
Freeze/Thaw	Alternate freezing and thawing of water in concrete pores	Concrete expansion and fouling Temperature at concrete surface Concrete cracking and spallation
Magnesium attack	Waterborne magnesium ions and complexes react with cement paste constituents causing concrete to expand and deteriorate	Concrete expansion and fouling Aqueous magnesium concentration Eh and pH at concrete surface

Table 4. Degradation mechanisms and parameters to consider for vegetative top cover.

Mechanism	Definition	Measurable Parameters
Water Erosion	Movement of cover material from normally occurring site precipitation	Precipitation characteristics Soil loss or movement Change in cover elevation
Wind Erosion	Movement of cover material from normally occurring site winds	Wind characteristics Soil loss or movement Change in cover elevation
Denudation	Vegetation stress leading to plant death without new plant growth	Vegetation characteristics Climatic conditions
Human Activities	Cover disturbance by primarily equipment operation and sample collection	Soil loss or movement Miscellaneous disturbance
Biological Intrusion	Animal or plant intrusion into the cover	Animal or insect burrow depth Plant root depth
Freeze / Thaw	Alternate freezing and thawing of near-surface soil moisture	Soil temperature Soil cracking or heaving Water ponding or excessive mud
Differential Settlement	Mechanical settling from changing weight and compaction of host materials, waste, vault, and cover	Change in cover elevation Cover movement

Table 5. Degradation mechanisms and parameters to consider for sand/gravel layer and drainage backfill.

Mechanism	Definition	Measurable Parameters
Sedimentation	Mechanical or hydraulic transport of finer grained particles in pore spaces	Bulk density/Porosity
Differential Settlement	Mechanical settling from changing weight and compaction of host materials, waste, vault, and cover	Change in cover elevation Horizontal continuity and thickness

Table 6. Degradation mechanisms and parameters to consider for clay low-permeability layers

Mechanism	Definition	Measurable Parameters
Biological Intrusion	Animal or plant intrusion into the cover	Animal or insect burrow depth Plant root depth
Differential Settlement	Mechanical settling from changing weight and compaction of host materials, waste, vault, and cover	Horizontal continuity and thickness
Shrink/Swell / Redistribution	Movement of clay particles usually caused by changes in water content	Horizontal continuity and thickness Bulk density/Porosity

4. MONITORING TECHNIQUES AND INSTRUMENTATION

Techniques and instrumentation used to monitor the performance of the engineered barriers are evaluated considering nine criteria.

1. Capability. A monitoring method should provide information concerning one or more of the parameters or conditions listed in Tables 2, 3, 4, 5 and 6.
2. Intrusiveness. The selected monitoring equipment installation and data collection activities should not significantly degrade performance of the LLWDF by intrusion into the engineered barriers.
3. Equipment and instrument reliability. Monitoring equipment and instruments should provide reliable data over the expected lifetime of the instrument. The monitoring equipment should provide predictable durability for the expected environment and be able to sustain routine field use.
4. Data quality. High quality data are representative of actual conditions. Representativeness can not be determined with low quality data.
5. Uniqueness. Unique interpretations of measurements may be attributed to no more than one field parameter or condition.
6. Suitability to automation. Manual data acquisition systems are relatively impractical for the long term. Properly operating automatic data acquisition systems are capable of collecting data from many monitoring instruments covering a large area.
7. Simplicity. If a complex method and a simple method both produce similar results, the simple method should always be employed for long-term monitoring.
8. Degree of development. Monitoring techniques that use standard methods and are well accepted should be given the highest consideration. Under-developed or recently-developed approaches could be more difficult to defend, but these approaches should not be rejected for this reason alone.
9. Cost-effectiveness. The selected monitoring techniques should provide relatively high cost-effectiveness.

The purpose of this report is not to identify monitoring techniques that are still in the experimental development stage. For this report, instrumentation recommended for use in the LLWDF monitoring system is either available or is considered to be easily within the state of the art. It is possible to develop an integrated monitoring program using existing technology as described throughout this section.

4.1 Inspection Procedures During Operational Monitoring Phase

The placement and quality of materials used during construction and operation of the LLWDF are critical to satisfactory long-term performance. These materials include steel containers, concrete, steel reinforcement, geosynthetics, and earth materials used for barriers.

High integrity containers encapsulating the waste need to be inspected during placement into the vault to ensure that they are sound. Visual inspection can determine whether degradation of the containers has occurred during storage. For greater confidence, nondestructive evaluation methods may be employed to check container integrity before they are moved into the vault.

Concrete and reinforcing steel should meet the requirements of the American Concrete Institute (ACI) for material properties, conformance to specifications, placement, and inspections (ACI, 1983). The concrete and steel material specifications are set by the structural engineer and may be verified by the procedures of the American Society for Testing Materials (ASTM), as cited in the ACI Code. For deleterious conditions, additives in the concrete mix are recommended to retard eventual decay of the structure (Clifton and Knab, 1989). Inspections of the concrete and steel will ensure that the intentions of the structural engineer are fulfilled. Particular attention will be paid to placement of the concrete. For structural stability of the LLWDF, voids in the concrete walls must be minimized.

Geosynthetics require special attention during placement and covering with backfill (Wright et al., 1987). A qualified inspector should be present during these critical operations. The following provisions must be made:

- Enough slack should be left in the geosynthetics so they are not subjected to any tension that could cause ripping as backfill materials are placed.
- Cobbles or boulders that may punch through any geosynthetics should be removed before installation.
- Fill materials should be inspected before and during placement to ensure that they are free of any debris or sharp objects.
- Seams in the geosynthetics should be inspected to ensure that they are made in accordance with the manufacturer's instructions.
- Any other provisions required by the manufacturer must be strictly followed.

Slopes located below the geosynthetics (adjacent to the backfill materials) must be designed so there is little potential for slumping toward the vault during operations. The design will be based on parameters determined during the initial geotechnical investigation of the site. Inspections should be made to ensure that these slopes are stable.

Drainage backfill material should be inspected before and during placement to ensure that it is suitable for the intended purpose. Tests may be performed on representative samples of the material where visual inspection does not verify that these materials will perform as required. Generally, the drainage characteristics of coarse materials can be easily predicted by visual inspection.

Other earth materials used during the operational phase of the LLWDF will require more attention. Factors relevant to performance include compaction, sufficient thickness of layers in the engineered cover, proper selection of filter materials, and slope of the cover.

Inspections will be required continuously during placement of barriers to ensure that appropriate materials and methods are used. The inspector may visually check that the height of the lifts are as specified by the engineer. Based on moisture/density relationships (Proctor compaction test) determined in the laboratory, the moisture content and compaction will be continuously checked to verify that the specifications are met. A nuclear densiometer should be used by the engineer and periodically verified by other tests [i.e. field density by sand cone (ASTM D-1556) and moisture content (ASTM D-2216)] for calibration.

If a soil is to be used for a filter in the engineered cover, it must meet two criteria. First, the soil to be protected (the base soil) must not be washed into the filter. Second, excessive hydrostatic pressure head cannot develop in the base soil (Das, 1984). Analysis of the grain size distributions of base and filter soils determines whether these conditions are met. Laboratory verification of the materials used for the filter and base should be made periodically during the operational phase at the discretion of a qualified inspector.

Inspection of the cover must be made to ensure that the slope meets the engineering specifications. If the slope is too steep, excessive erosion will occur over the lifetime of the LLWDF. If the grade is insufficient, ponding of water on the surface may occur and result in possible infiltration into the vault.

4.2 Surface Monitoring Using Traditional Methods

4.2.1 Purpose. Conditions indicating rates and/or degree of infiltration, erosion, biological intrusion, human disturbance, freeze/thaw heaving, and differential settlement can be monitored using traditional surface techniques without compromising the cover's performance. Many examples of applications that are important to LLWDF monitoring are available. Hostetler et al. (1981) evaluates the application of surface surveillance methods to studies of water erosion at LLW disposal sites. Nyhan and Lane (1986) monitored surficial conditions in conjunction with surface hydrology and meteorology to substantiate the use of the universal soil loss equation. Cadwell et al. (1989) and Wing (1988) developed field procedures to calibrate biological intrusion models.

Surficial degradation processes are interrelated and should be monitored as such. For example, differential settlement and denudation are often direct precursors to enhanced erosion rates. Also, erosion and differential settlement affect the quantity and/or distribution of runoff and thus water budget analyses.

4.2.2 Frequency. Three factors should be considered when selecting monitoring frequencies:

1. Monitoring frequencies should consider the relative importance of data with respect to cost of data collection. Many surveillance-type monitoring methods are labor-intensive and require manual data processing. Thus, monitoring frequency should be as low as possible based on cost weighed against beneficial uses of the frequently collected data. Palmer and MacKenzie (1985) describe such an analysis.

2. Monitoring frequencies should be minimized to reduce damage caused by monitoring activities. Many surface techniques ideally require relatively frequent direct access to a sometimes fragile vegetative cover. Unfortunately, frequent data collection may disturb the fragile cover, especially if protocol involves regular sampling locations.

3. Monitoring frequencies for highly variable environments should be well suited to the conditions and be flexible enough to recognize important monitoring periods. For example, humid environments may require frequent water erosion monitoring throughout the year. Arid sites may receive the majority of precipitation in the winter as snow. Monitoring water erosion during dry periods may be unnecessary; however, wind erosion monitoring may be highly appropriate.

4.2.3 Methods.

4.2.3.1 Environmental Surveillance. Several important degradation processes are evaluated using data obtained from the cover's surface. Many parameters required to create models that describe erosion, biological intrusion, and differential settlement are measurable using surveillance methods. Also, surface runoff and vegetation characteristics related to evapotranspiration are necessary surveillance parameters to estimate net infiltration through the use of water budget analyses. Surveillance involves visual inspection and various traditional equipment and analysis to measure the parameters listed in Table 7. Equipment may include items such as measuring tapes, cameras, weirs, and rill-meters.

Table 7. Typical parameters associated with degradation mechanisms causing changes at the surface

- Meteorologic conditions
  - Rainstorm intensity and duration
  - Wind velocity
- Drainage characteristics
  - Drainage patterns
  - Rill and gully characteristics
  - Hydraulic roughness
  - Surface runoff rates
- Soil properties
  - Particle size and shape distribution
  - Particle cohesion
  - Soil bulk density
  - Soil structure and aggregation
  - Organic matter content
  - Chemical properties
  - Aggregate strength and stability
- Microtopography
  - Elevation
  - Slope aspect, length, and shape
- Vegetation canopy
  - Canopy type
  - Average canopy height
  - Percent canopy cover
- Vegetation root system
  - Extent and length
  - Soil stabilization potential
  - Water extraction potential
- Vegetation habitat characteristics
  - Succession species
  - Seasonal changes
  - Species hardiness
- Animal habitat characteristics
  - Succession species
  - Burrow extent and depth

One important surficial degradation process is erosion. The Universal Soil Loss Equation (USLE) statistically predicts soil erosion based on erosion parameters identified during surveillance monitoring (Hostetler et al., 1981). It was designed to predict long-term, average soil losses caused by runoff. Nyhan and Lane (1986) provide guidance on using the ULSE at waste burial facilities. The major parameters needed to solve the USLE are included in Table 7. The USLE is algebraically represented as

$$A = RKLSCP \qquad (3)$$

where

A = soil loss per unit area

R = rainfall and runoff factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover and management factor (vegetation and surface cover)

P = support practice factor (contouring, terracing).

Periodic inspections (based on the frequency factors discussed earlier) should be performed using a systematic approach to inspect the entire disposal site and surrounding area. This approach provides a means of detecting both changes over time and spatial comparisons of one region of the site to another. Further, surveillance is helpful to guide the implementation of other monitoring methods.

Environmental surveillance is perhaps more sensitive than other types of monitoring to the subjective judgment of the inspector. Experience has shown that this can introduce difficulties in data interpretation, particularly for long-term programs that depend on a series of individual inspectors (Mar et al., 1985). Therefore, site-specific inspection protocols must be established to ensure a consistent approach. In addition to routine monitoring, inspections during or immediately after heavy rains, high winds, or spring thawing may lead to valuable insights on the physical response of the site. Accurate recordkeeping is especially important for environmental surveillance programs. Any changes or anomalies must be properly documented for comparisons with future inspection results, perhaps by a different inspector.

4.2.3.2 Meteorological Data Collection. Meteorological data are collected at LLWDFs to allow an estimation of net infiltration. The amount of precipitation, evaporation, and transpiration needs to be determined to allow application of water balance analysis methods to obtain an estimate of the amount of water that infiltrates the surficial cover [Equation (2), Section 3.1]. Meteorological data are also needed to assess surficial degradation processes such as wind and water erosion, vegetation denudation, and freeze/thaw cycles.

There are several approaches to determining evapotranspiration rates from meteorological data. Evapotranspiration can be determined as the residual in an energy balance equation. The Bowen (1926) ratio method is probably the most widely used of the energy balance methods. Other methods are based on the upward transfer of mass in the atmosphere (aerodynamic profile methods) or combinations of energy balance and aerodynamic profile methods. The energy balance and aerodynamic profile methods are currently used at the Sheffield site to estimate evapotranspiration (Healy et al., 1986).

These evapotranspiration estimation techniques require a variety of meteorological data. The energy balance equation states that the energy arriving at the Earth's surface goes into heating the air, heating soil, and evapotranspiring available water. The required information is net radiation, soil heat flux, and vertical gradients of air temperature and water vapor pressure; net radiation is incoming shortwave and longwave radiation minus reflected shortwave and emmitted longwave radiation. Wind is an important requirement for evapotranspiration. Without wind, the atmospheric boundary layer would reach saturation, and evapotranspiration would cease. Although wind speed is not incorporated into the Bowen ratio method, it is an integral part of aerodynamic profile methods.

Meteorological instruments vary substantially in cost, precision, and accuracy. The meteorological properties reviewed below have been successfully monitored at current LLWDF sites in both humid and arid settings (Cahill, 1982; Foster et al., 1984; Healy et al., 1986; Nyhan, 1989; Pittman, 1989). A meteorological station should be operated at the representative test area with additional instruments at the actual facility.

Precipitation in the form of rain, hail, and snow should be totaled frequently depending on precipitation characteristics. Routine tipping-bucket rain gages or weighing-type rain, hail, and snow gages measure precipitation volume per time. Several gages should be situated throughout the disposal area and test area to compensate for spurious readings, gage failure, and/or spatial variability. Wind circulating upward past the gage causes the most significant errors associated with precipitation measurement (Linsley et al., 1982). Windbreaks as described by ASTM (1989) should be employed for a few precipitation gages at the test area.

Wind speed and direction should be averaged frequently depending on wind characteristics. Horizontal wind speed should be measured at several elevations using 3 or 4 cup anemometers (ASTM, 1989). A potentiometric wind vane provides wind direction. Instrument accuracy and precision is high, however, only for the specific instrument location. Wind speed and direction instruments should be located to monitor all representative topographic regions.

Water vapor pressure (often expressed as relative humidity), barometric air pressure, and ambient air temperature should be averaged frequently depending on climatic conditions. Ventilated psychrometers should be operated at various heights above land surface to determine both humidity and temperature gradients (ASTM, 1989).

Net radiation can be measured directly or in its individual components (incoming and outgoing shortwave and longwave). Incoming and reflected solar radiometers or specifically precision spectral pyronometers should be used at various elevations, especially from 1 to 2 m. Successful implementations are described by Pittman (1989) and Healy (1989). Soil surface temperature and soil heat flux should be measured at various locations around the cover using temperature sensors as described by Taylor and Jackson (1986) and heat-flux plates as described by Fuchs (1986).

4.2.3.3 Surveying Methods and Instrumentation. Surveying methods are used to monitor the magnitude and rate of horizontal and vertical deformations of the cover surface and accessible parts of buried instruments. When buried geotechnical instruments are used to monitor deformation (as described in Section 4.5), surveying methods are also used to relate measurements to a common datum.

Surveying techniques and instruments are available (such as electronic distance measurement equipment) that are accurate enough to monitor differential settlement as expressed at surface measuring points of a LLWDF (Davis et al., 1981). Instrument accuracy of ±10 - 30 mm will likely suffice to monitor differential settlement at a LLWDF based on similar situations for performance monitoring of earthen dams (Dunnicliff, 1988). Measurement accuracy is controlled by the choice of surveying technique and by characteristics of reference datums and measurement points. Survey instrument technology is well established, and most reputable manufacturers include a statement of accuracy in their instrument specifications, which can be relied on if the instrument is calibrated and operated in accordance with the instructions (Dunnicliff, 1988).

Measuring points (fixed reference datums) should be located on the surface of the cover. The measuring points could be fixed within the vegetative top cover or fixed directly to the concrete vault or other locations beneath the vegetative top cover with a bar made of a temperature compensated alloy during construction (Davis et al., 1981). Bars intruding through engineered barriers should be severely limited because they will cause difficulties in construction of final cover and allow a path of preferential water flow.

Several difficulties may exist when interpreting measurements. Measurement points anchored within the upper part of the LLWDF cover should be seated below the zone of frost heave and seasonal moisture changes (Dunnicliff, 1988). Unfortunately, many of the measurement points will be anchored within the seasonal moisture variation zone (to minimize intrusiveness), and some movement may occur without indicating subsidence. Other causes of movement (reportedly ranging to 8 cm) include clay shrinkage and swelling phenomena (Dunnicliff, 1988).

Dunnicliff (1988) predicts the satellite-based NAVSTAR Global Positioning System is likely to replace optical or trigonometric leveling to determine the long-term settlement of dams. The high cost must be compared to its advantages of accuracy (down to several millimeters) and greatly reduced need for access to the cover's surface (Laurila, 1983).

4.2.3.4 Bioindicators. Bioindicators will provide site-specific evidence of plant root and animal burrow intrusion. For example, warning markers such as colored beads could be added below a protective cobble barrier during facility construction. Animal intrusion to that depth would be demonstrated by detecting a warning marker at a burrow entrance (Wing, 1988). Plant roots may also penetrate through the protective barrier and eventually die and form small continuous water conduits or puncture a membrane geosynthetic. Plant uptake of rare earth metals placed (during construction) just below the protective barrier or just below a geosynthetic could be detected by chemically analyzing the plants. Visual inspection and sampling for bioindicators could be conducted in conjunction with the biota portion of the radionuclide detection monitoring program. Accuracy depends on the representativeness of sampling and minimum level of bioindicator detection.

4.3 Surface Monitoring Using Remote, Sensing and Photogrammetric Techniques

Three major sectors of the electromagnetic spectrum are used for remote sensing: ultraviolet to near infrared (visible light), thermal infrared, and microwave (Sabins, 1987). These sectors of the spectrum can be used to image a terrain in many ways; the best known is aerial photography. Image data are not always recorded directly on film. Various types of scanners are also used that produce an electronic output. The data generated by such remote sensing systems can be transmitted from aircraft or satellites and then reconstituted into digitized images.

Remote sensing and photogrammetry are still developing technologies, with refinements being made in data collection and image analysis to differentiate between the spectral responses (Sabins, 1987). High resolution data at a cost-effective price are likely to be obtained by the time of LLWDF closure. (Lyon, 1987).

4.3.1 Purpose. Remote sensing and photogrammetric techniques offer completely nondestructive data collection capabilities by recording surficial electromagnetic properties from aircraft or satellites. Interpretation of remote sensing and photogrammetric data yields large-scale estimates of surficial conditions such as soil moisture, organic matter content, erosion patterns, depressions and/or ponding, snowpack characteristics, and vegetative stress. The purpose of remote imaging and photogrammetric techniques is to provide complete coverage of the LLW disposal site. This coverage allows interpolation between localized measurements taken with land-based instruments. Ground-based measurements and reference data are usually needed to assist in analysis of photographs and remotely sensed images. Analysis can often provide more quantitative records than land-based surveillance methods alone, allowing more quantitative comparisons of changes over time. This perspective can recognize relatively subtle large-scale anomalies.

4.3.2 Data Collection. Data are recorded either on film (photogrammetric) or digitally (remote sensing). Photogrammetric interpretation, commonly practiced for geologic interpretations, is usually dependant on the trained subjective judgment of an interpreter. Remote imaging is recorded digitally and is processed to produce a grid map of the recorded signal characteristics. Multispectral imaging is available. Remote imaging data or digitized photogrammetric data are well suited to a geographical information system (GIS) format as discussed in Section 6.

Photogrammetric and remote sensing data are available from sources such as National Cartographic Information System managed by the U.S. Geological Survey, LORAN managed by the U.S. EPA, Data Center managed by the National Aeronautics and Space Administration (NASA), and other domestic and international commercial organizations (Sabins, 1987).

4.3.3 Photogrammetric Techniques. Photogrammetry may be useful to observe movements in the cover. This method can identify overall deformation patterns. Lateral motion of the materials constituting the engineered cover may indicate an impending failure. Photogrammetry may be used to identify the first signs of failure, and additional data could be analyzed to determine if a problem exists.

Photogrammetric techniques record emitted electromagnetic waves on film. Photographs provide the capability to "see" changes in topography, vegetation patterns, etc. Monitoring with photogrammetric techniques involves the evaluation of photographs to decide upon reactions in response to observed changes.

Disadvantages include lower resolution and more limited multispectral capabilities compared to sophisticated remote sensing (Sabins, 1987). Also, clouds will block direct vision when filming in the visible spectrum.

4.3.4 Remote Sensing. Water is unique in that it is near the extremes in its thermal and dielectric properties. As a result, the corresponding properties in the soil are highly dependent on its moisture content. These properties are accessible to remote sensing through measurements at the thermal infrared (≈ 10 m) and microwave (≈ 1 to 50 cm) wavelengths. Remote sensing methods respond to water content within the upper 5 to 10 cm of the surface (Schmugge et al., 1980).

4.3.4.1 Thermal Infrared Sensing. The amplitude of the diurnal range of soil surface temperature is primarily a function of thermal conductivity, heat capacity, and meteorological factors (solar radiation, air temperature, relative humidity, and wind). A soil's thermal conductivity and heat capacity properties are highly dependent upon its moisture content. These properties are measurable by remote sensing from aircraft or satellites at the thermal infrared wavelength (10 m). The measured diurnal range indicates some combination of soil moisture and surface evaporation (Reginato et al., 1976; Schmugge, 1978).

As a LLWDF cover will have a vegetative canopy during the active growing season, the canopy temperature and not the soil temperature will control the diurnal temperature range. However, the difference between canopy temperature and ambient air temperature is an indicator of vegetation stress (Ehrler, 1973). Thus, if the vegetation stress depends mostly on soil moisture, the canopy temperature reflects an effective soil moisture over the rooting depth (Reginato et al., 1976).

4.3.4.2 Microwave Sensing. Active and passive microwave measurement methods are two types that are applicable to LLWDF. Active microwave measures the radar back-scattered coefficient, and passive microwave measures the microwave emission or brightness temperature. The dielectric properties of a material are strong functions of its moisture content. Since the materials' dielectric properties determine the propagation characteristics for microwaves in the material, they will affect the emissive and reflective properties at the surface, which can be measured by passive or active microwave techniques.

This physical relationship between the microwave response and soil moisture, plus the ability of the microwave sensors to penetrate clouds, makes them very attractive for use as surface soil moisture monitors (Schmugge, 1978). Bernard et al. (1986) showed the utility of active microwave techniques by estimating spatial drying variations because of different drainage properties in the layers directly beneath the surface layer. Obviously, these interpreted results could be beneficial for evaluating performance of the drainage layer as a large-scale measurement over the entire cover.

4.4 Subsurface Hydrologic Monitoring Using Tracers and In Situ Equipment

4.4.1 Purpose. Localized data are collected by installing monitoring instruments within the subsurface engineered barriers. These data can be interpreted to infer the barriers' local performance based on hydraulic head and water content distributions [Equation (1), Section 3.1]. These data can be related to surface estimates of seepage and to calibrate water budget models [Equation (2), Section 3.1]. Localized pore water pressure is also necessary to estimate effective stress [Equation (3), Section 3.2]. Tracers can help determine seepage rates and directions. In situ measurements can be used with geophysical data to allow a more unique and accurate geophysical interpretation.

4.4.2 Location and Installation. Because instrument installation and augerholes can degrade the function of the barriers, monitoring through the cover should be minimized. The resulting incomplete coverage can be remedied by surficial and geophysical monitoring. The instruments should also be installed at a representative test area as described in Section 4. Four recommendations are common to most hydrologic monitoring instruments:

- Use of instruments requiring access holes through engineered barriers should be severely limited.
- Instruments should be installed to allow replacement, if possible.

- Instrument leads should be zigzagged through cover to allow for subsidence and minimize routes of preferential flow.

- Instruments should be carefully installed to provide for an excellent contact between sensor/filter and material.

The ability to replace and/or calibrate instruments is important. Rogue and Binnall (1983) studied the reliability of commercially available instruments and discovered that many common ones last for only 14-18 months. Additionally, most unsaturated zone instruments have not been tested for reliability over time.

Many of the instruments have limited operating ranges within unsaturated regions. For example, Figure 4 shows typical pressure head ranges for four common instruments. Engineered barriers may have different water contents, so specific instruments are more applicable in some barriers than in others. For example, tensiometers may not be applicable to rapidly draining layers because the pressure head will often be significantly less than atmospheric, which is indicative of very dry conditions. Wherever possible, several instruments and instrument types should be placed adjacent to one another.

4.4.3 Frequency. Monitoring frequency depends mainly on precipitation conditions and practical limitations of computer storage. By correlating the collection intervals with precipitation events, the use of data storage can be optimized. For example, at either a humid or arid site, monitoring frequency should increase during rainy or snow melt periods. After a recharge event, monitoring should last until moisture redistribution becomes imperceptible. If the Darcy method or some similar method is used to estimate seepage then water content or pressure head measurements must be made frequently enough to ensure that no wetting front pass undetected (Healy, 1989). The rate of water redistribution usually decreases rapidly over the course of several days or weeks (Hillel, 1982).

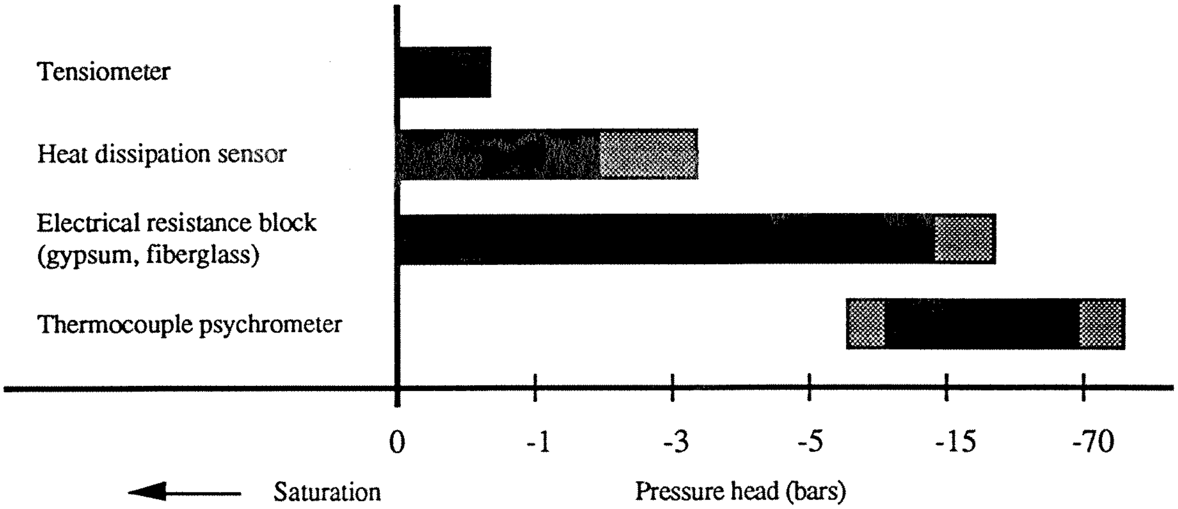

Figure 4. Approximate pressure ranges for unsaturated zone instruments. Solid shading indicates pressure range over which the instrument can usually provide quality data. Stippled shading indicates questionable operating range (Campbell and Gee, 1986; Rawlins and Campbell, 1986; Stannard, 1986).

4.4.4 Data Collection and Documentation. Instruments can be equipped with automatic data collection systems. Data loggers are commercially available for each type of instrument. Since typical ranges of voltage, amperage, and resistance are recorded from the instruments, a common recording device should be applicable to all instrument types, thus, removing variability between recording devices.

4.4.5 Limitations. Installed instruments have many significant limitations including

- Instruments and augerholes through cover have a high potential to interfere with the engineered barrier's function.
- Instruments are left in place with limited replacement options available.
- Long term reliability (greater than 5 years) of instruments employing porous sensors and high air entry filters can not be quantified.
- Instrument drift will cause changing calibration curves.
- Material specific calibration curves are necessary for several instruments.
- Some kinds of instrumented systems have long hydrodynamic time lag.

Other significant limitations specific to certain instruments are identified in the following section.

4.4.6 Equipment

4.4.6.1 Open Standpipe Piezometers. Piezometers measure the pressure head in saturated media. A piezometer is simply a cased augerhole with a screened interval (low air entry filter) open below the water table. The water level inside the well represents an integrated average pressure head along the screened interval. Water levels can be measured with a pressure transducer. Multipoint piezometers can be assembled with a packer above and below each piezometer to create a seal. An innovative multilevel system has been designed by Pickens et al. (1981) and Cherry and Johnson (1982) and can also be adapted for ground water sampling (Hitchman, 1988).

Advantages include high reliability and multiple uses of cased hole. Disadvantages include high intrusiveness after construction, interferences and inferior compaction during engineered barrier construction, long time lag (especially in low-permeability materials), and filter clogging.

Location and construction of piezometers should allow alternative uses and not compromise the performance of engineered barriers. Piezometers should probably not be installed through any engineered barriers. Stainless steel or other inert casing materials should be used if holes will be used for chemical analysis. Geophysical techniques that use augerholes often require certain types of casing materials.

4.4.6.2 Tensiometers. Tensiometers measure the pressure head in unsaturated media over the range of 0 to -0.85 bar (Hillel, 1980; Stannard, 1986). The essential elements of a tensiometer are a high air entry porous cup connected with tubing to a vacuum gage; all are filled with water. When the porous cup is buried in unsaturated media, the medium draws water through the cup until water tension inside the cup equals the surrounding pressure head in the surrounding media. The tension is transmitted through the water-filled tube to an accessible vacuum gage (transducer) and is recorded automatically as voltage. Design features include a flushing system for removal of entrapped air (Stannard, 1986).

Tensiometry is the most reliable method to measure pressure heads less than atmospheric. However, installation requires careful attention to ensure good contact between the porous cup and surrounding material. Interferences can include

- Air temperatures that have an effect on water density and pressure head measurements.
- Vacuum leaks that cause incorrect gage readings, water level changes, and hydraulic head calculations.
- Air bubbles that clog the porous cup and require periodic flushing.

4.4.6.3 Pneumatic and Vibrating Wire Diaphragm Piezometers. Pneumatic and vibrating wire transducers housed in a thick-walled cylinders respond to pore water pressure through high air entry filters. These instruments can be situated within engineered barriers with leads projecting horizontally through the same engineered layer, causing minimal disturbance through engineered barriers. However, installation requires careful attention to ensure good contact between the filter and surrounding material.

4.4.6.4 Thermocouple Psychrometers. Thermocouple psychrometers measure the relative humidity of pore air. The relative humidity is related to unsaturated pressure head by the following relationship:

$$\Psi = RT \ln(H_r / 100) \qquad (4)$$

where Ψ is the pressure head, R is the ideal gas constant; T is the absolute temperature; and H_r is the relative humidity (Hillel, 1980). Thermocouple psychrometers consist of a thermocouple, reference electrode, heat sink, and chamber covered porous bulb as described by Rawlins and Campbell (1986). The devices can be interfaced with automatic data loggers set to read output voltage.

In situ water pressure measurements are possible for the range of -10 to -70 bars, permitting the determination of water content in the very dry ranges expected for drainage layers (Rawlins and Campbell, 1986). As with other vadose instruments, installation requires careful attention to ensure good contact between the porous bulb and surrounding material. Thermocouple psychrometers can be calibrated to water content and pressure head for each engineered component based on textural changes; however, vapor pressure actually equilibrates with nearby soil tension and not nearby water content (Meyn and White, 1971).

4.4.6.5 Electrical Resistance Blocks. Electrical resistance blocks are used to measure both pressure head and water content, but pressure head measurements are preferred (Campbell et al., 1986). Although resistance blocks respond to internal water content, the internal water content actually equilibrates with nearby soil tension and not nearby water content. Separate curves are required for each component based on textural changes. Electrical resistance blocks can operate in the pressure range of 0 to -15 bars; however, saturated conditions reduce the useful lifetime of gypsum-type blocks because of increased rates of internal dissolution with resulting instrument drift (Campbell and Gee, 1986).

Resistance blocks are commonly made of gypsum, nylon, or fiberglass. Gypsum block maintains a nearly constant internal electrolyte chemistry but slowly dissolve depending on the water content. Dissolution changes the internal pore structure and causes instrument drift. Inert materials such as nylon or fiberglass dissolve much slower, but the electrical resistance changes with both solution electrolyte chemistry and water content. Blocks made of such inert materials are highly sensitive to even small variations in salinity of the soil solution (Hillel, 1980). The electrical resistance of blocks also changes with temperature.

4.4.6.6 Heat Dissipation Sensors. Heat dissipation sensors are used to measure both pressure head and water content as described by Laney et al. (1988). The sensor consists of a diode with a heating circuit, a porous matrix, and temperature sensors (thermistors). Measurements are based on the relationship between the rate of heat dissipation and the water content within a porous matrix. Although heat dissipation sensors respond to internal water content, the internal water content actually equilibrates with nearby soil tension and not nearby water content. Sensors are calibrated to the pressure head specific to textual properties within each engineered barrier using a pressure plate apparatus. Pressure head measurements are independent of pore water salinity and texture over the range of 0 to -15 bars (Phene et al., 1971).

4.4.6.7 Temperature Sensors. Seepage rates may be inferred from the vertical temperature distribution based on the premise that ground water moving vertically influences the temperature gradients associated with geothermal heat flux to the surface (Bredehoeft and Papadopulos, 1965). Temperature changes below the extent of ambient diurnal temperature variation can be related to seepage rates and patterns. For example, Sammis et al. (1982) estimated deep seepage rates based upon the distortion of normal temperature profiles in the zone below 15 m.

Temperature is measured with other instruments (such as heat dissipation sensors and thermocouple psychrometers) and could be measured independently. Commonly available temperature devices are small, simple, and durable. Long-term reliability is high and depends on the corrosion resistance of the sensors and related electrical lines. Protective tubes are available to guard from mechanical damage and corrosive environments. The precision over temperature ranges expected at a LLWDF for resistance temperature devices, thermistors, and thermocouples is approximately ±0.10, ±0.15, and ±0.6 °C, respectively (Rogue and Binnall, 1983). Such precision is sufficient for monitoring purposes.

4.4.7 Tracer Studies. Tracer studies may provide information to determine the direction and velocity of seepage for unsaturated conditions and ground water movement under saturated conditions (Davis et al., 1980). Tracers could be periodically applied at the surface, periodically injected into monitoring wells, and/or added to engineered barriers during construction. Failures of tracer studies are most commonly a result of an incorrect choice of tracers, insufficient concentrations of tracers, and a lack of understanding of the water movement (i.e., incorrect detection locations). Although tracer studies require detector location, they do not introduce additional reasons for intrusion. If conducted in a thoughtful fashion, tracer studies can provide information on performance that is not obtainable through any other method.

An ideal ground water tracer is nontoxic, inexpensive, moves with the water, is easy to detect in trace amounts, does not alter the natural direction of the water flow, is chemically stable for a desired length of time, is not present in large amounts in the water being studied, and is neither filtered nor sorbed by the solid medium through which the water moves. Some useful tracers are inorganic salts, fluorocarbons, and dyes. Radionuclides are often almost ideal; however, because their use may significantly disrupt the radionuclide monitoring program, they are not further considered. Tracers should be selected for LLWDF monitoring to meet the criteria noted above as determined by the specific type of test.

As an example application, Mills and Razor (1988) added various chemical dyes and inorganic salts to engineered barriers of a demonstration trench in a humid environment. A specific tracer (A) was added above the upper low-permeability layer, and a different tracer (B) was added below the lower low-permeability layer. If tracer A is detected in water from the waste drainage collection system, then the upper infiltration barrier failed. If tracer B is detected in water from the waste drainage collection system then the lower infiltration barrier failed. Finally, if tracer-free water is collected, it would indicate water entry via the sidewall infiltration barrier.

4.5 Subsurface Physical Monitoring Using In Situ Equipment

4.5.1 Purpose. There are two types of in situ measurements to monitor LLWDF stability. The first determines stress (or pressure) acting on points within the system. As shown in Equation (3) (Section 3.2), both pore water pressure and total stress should be measured to estimate effective stress. The second is determining deflections or displacements of components within the system.

4.5.2 Location and Implementation. Several considerations are made for selecting locations of geotechnical instrumentation at the LLWDF. Modes of failure must be considered during operational and long-term phases. To maximize the information obtained for a given cost, the instrumentation should be placed so that parameters specific to these modes of failure are measured. For example, pore water pressure should be measured just above the low permeability layer because it is a potential failure surface relative to sliding failure of the cover.

The same limitations imposed on the hydrologic monitoring equipment apply to geotechnical methods used to observe stability parameters. Particular attention should be made in setting up the monitoring program to avoid intrusion through the engineered barriers. Additionally, the monitoring design should implement more than one method to measure each parameter. Some instrument redundancy is necessary to verify that all components of the monitoring system are functioning properly.

Monitoring pore water pressure to evaluate stability is most effective at the following locations within the LLWDF:

- At the interface between the drainage material and low permeability clay layer or geomembrane at the base of the engineered cover
- Within the slopes adjacent to the drainage backfill and outside of any geosynthetic

- Below any geosynthetics located beneath the entire structure.

4.5.3 Frequency. Monitoring frequency depends on operations, natural conditions, and the need for data. During the operational phase of the facility, monitoring should be performed as required by a qualified engineer. If wastes are placed in the vault at a rapid rate, daily data may be required to ensure that significant differential settlements are avoided. Slopes adjacent to the backfill material should also be monitored on a frequent basis to ensure safety and to establish a record for postoperational monitoring.

During long-term monitoring of the LLWDF, the frequency of data collection should be based on trends and natural events. For example, if settlement occurs immediately after the operational phase but diminishes over time, then the intervals between making measurements may be increased accordingly. However, if a high precipitation event or other natural occurrence significantly increases the influx of water to the system, data should be gathered to ascertain what effects this event may have on the parameters that determine stability.

4.5.4 Methods

4.5.4.1 Effective Stress Evaluation. As shown in Equation (3), Section 3.2, both total stress and pore water measurements are needed to calculate effective stress. Pore water pressure, as discussed in Section 4.4, is measured using hydrologic equipment such as open standpipe piezometers, tensiometers, and pneumatic and vibrating wire piezometers. Total stress is generally determined from calculation of the weight of overburden materials. However, in some cases, it is worthwhile to directly measure this parameter.

Total stress measurements may be facilitated by the use of earth pressure cells. These should be located at the same elevation as the piezometers below the entire structure. Each earth pressure cell should be placed in exactly the same manner and at the same elevation. This will allow for comparisons of the stresses below the vault at different locations in plan view. Data generated by these cells and pore water pressure measurements could be used to evaluate load distributions in the vault and the soil below. This information would primarily be used to prevent differential settlement during the operational phase of the LLWDF.

Earth pressure cells have many inherent problems. These mainly arise as the result of incompatibility of the cell with the surrounding environment. The cell itself will not respond to pressure changes in the same manner as the surrounding earth materials. In addition, installing the earth pressure cell may create stresses that are dissimilar to those in the surrounding materials (Terzaghi and Peck, 1967). Care must be taken to follow the manufacturer's instructions precisely if the earth pressure cell is to function as intended. For the LLWDF, the earth pressure cells could be installed in one lift of the relatively impervious layer below the geosynthetic. Care should be taken that this lift and others above the cells are uniform in compaction and thickness.

4.5.4.2 Slope Indicators. Another method for monitoring the stability of the engineered cover is by using slope indicators. This may be accomplished by installing slotted casing along several points within the cover. Deflections of the casing will occur over time and may be measured with an inclinometer. The casing pipes are permanently installed, and one inclinometer may be used to measure angular displacements in each. The slots in the casing orient the direction of the inclinometer so that the same parameter is measured each time.

4.5.4.3 Strain Gages. Strain gages may be installed in the concrete barriers to provide information on deformations of the vault and base slab. These data may be used to supplement other data on differential settlement of the vault or may help identify weaknesses in the structure that develop from long-term deterioration. Strain gages should be used to measure compression in the concrete. Large tensile stresses or cracked tensile sections do not register accurately on these types of gages (Dunnicliff, 1988). Remote readout for these gages is an essential requirement. For this application, vibrating wire type gages would be among the most suitable.

4.6 Subsurface Chemical Monitoring

4.6.1 Purpose. In the context of performance monitoring, the purpose of sampling pore gas and pore water can be summarized by five functions:

1. Determine pore solution chemistry in terms of potential degradation of concrete and geosynthetics
2. Determine pore solution chemistry in terms of radionuclide transport
3. Determine pore solution specific conductivity in terms of changing bulk electrical resistance
4. Characterize the impact of LLWDF on solution chemistry
5. Detection of water or vapor transported tracer.

In the context of a total monitoring program, radiological and chemically hazardous constituents will be monitored (detection monitoring). Monitoring locations and frequency will be dictated for the detection monitoring program. Presumably, performance monitoring will be integrated with a detection monitoring program (Denham et al., 1988; Sedlet and Wynveen, 1989). Sample collection methods and equipment will be similar for performance monitoring and detection monitoring, so vastly different methodologies are not expected.

Several degradation mechanisms specific to geosynthetics and concrete are consequences of chemical reactions between pore water solutes and various constituents of geosynthetics and concrete (Tables 2 and 3, Section 3.3). Many of the reactions may be biologically mediated. The composition of the aqueous phase immediately surrounding and within the cements and geosynthetics will affect the durability of the concrete and geosynthetics.

Specific rates of degradation for certain chemical environments are not known. Standard testing protocols rely upon data derived from exposing concrete or geosynthetic materials to high concentrations of chemicals at elevated temperatures for very short periods of time. Additional knowledge is clearly needed because of the influence of low-concentration, ambient temperatures, and long exposure on the geosynthetics and concrete.

4.6.2 Location. Useful pore gas and pore water samples could be obtained from five general regions:

1. Near-surface pore space and precipitation. Chemical analysis of precipitation or near surface pore water or gas gives the initial chemistry of recharge water. "Initial conditions" used together with known mineralogy of engineered barriers will provide valuable information. Near surface sampling activities are the least intrusive of all direct sampling methods.
2. Near the concrete and geosynthetics. The disposal facility will likely have some sort of drainage and pumping system (at least over the short term) within the vault and above low-permeability layers. Such drainage water may be the only means of sampling water near the concrete and vault.
3. Within the concrete pores. Chemical degradation of concrete depends primarily on the aqueous chemistry within the pores. Such data would be beneficial. However, collecting pore water samples is considered to be prohibitively intrusive. Conditions within the concrete walls can only be inferred through the results obtained by removing concrete "coupons" at the representative test area (Section 4).
4. Below the facility (for either saturated or unsaturated conditions). Pore gas and water samples should be taken after water has percolated through and around the disposal facility. These samples indicate "final conditions." Depending on depth to the water table, this may be in the unsaturated zone, perched water zones, or at the water table.
5. Distant regions not affected by the facility. The purpose of distant sampling is to determine the naturally occurring temporal variability. This background sampling can be used to understand the impact of a LLWDF on solution chemistry.

4.6.3 Frequency. Frequency and timing of sample collection depends mainly on three interrelated factors: surface infiltration characteristics (quantity and timing), seepage velocities, and aquifer velocities.

Pore water chemistry can be extremely variable over short time periods. Vadose water sampling frequency may be limited by the availability of water in dry conditions. If water is pumped from sump lysimeters of drainage collection systems on an intermittent basis, then the samples could be collected based on pumping intervals. Pumping rates should not exceed seepage rates, or natural flow will be altered resulting in a nonrepresentative sample.

4.6.4 Sample Collection and Analysis. Before the sample has been taken, it must be decided which key parameters will be measured at time of collection and which parameters will be analyzed in the laboratory some time later. Depending on the laboratory analysis parameters, appropriate techniques of preparation, preservation, and storage must be selected to minimize changes in the chemical composition of the sample between the time of collection and time of analysis (EPA, 1983; American Public Health Association et al., 1989).

Table 8 identifies the parameters that could be monitored to evaluate general chemical characteristics of the pore water. Chemical analyses of water usually report the total quantity of a particular element or ion without indicating its actual form in solution. However, dissolved elements or ions are present in one or more specific solute species. For example, complex ions are solute species derived from two or more single ions of opposite charge. The process of speciation, or measuring concentrations of all major solute species of a particular ion, is necessary to calculate chemical thermodynamic conditions. Knowledge of equilibrium conditions can result in estimations of, for example, the partial pressure of CO_2.

Many chemicals are important to concrete and geosynthetic durability and should be measured in the sample or calculated from thermodynamic equilibrium models. In general, most acids will attack cement, steel concrete reinforcement, and geosynthetics (Portland Cement Association, 1986; Richardson and Koerner, 1987). Salts and alkalies known to cause concrete degradation include salts containing sulfate, bisulfite, cyanide, dichromate, flouride, hexametaphosphate, nitrate, or chloride ions; sodium perborate; sodium perchlorate; potassium persulfate; sodium phosphate; thiosulfate; ammonium superphosphate; and borax (Portland Cement Association, 1986).

Table 8. Parameters that describe general chemical characteristics

Index Parameters	Cations	Anions
Specific conductance	Calcium	Sulfate
pH	Magnesium	Chloride
Eh	Sodium	Flouride
Dissolved Oxygen	Potassium	Nitrate
	Iron	Bicarbonate
		Carbonate

4.6.5 Techniques and Equipment Used to Collect Samples. Soluble solutes in the pore water of the vegetative top cover, drainage layers, and backfill surrounding the vault can be determined or estimated from measurements made (a) using extracts on removed material samples, (b) using samples of removed pore water, (c) in situ, using buried salinity sensors, and (d) in situ, using geophysical techniques. Pore gas samples will add valuable information about pore solution chemistry. Extracts on removed material samples may be conducted at the actual facility and the surrogate facility. Applications of geophysical techniques to water quality are discussed in Section 4.7.

4.6.5.1 Monitoring Wells. Monitoring wells are used to obtain water samples under saturated conditions. Many guidance documents and procedural manuals are available that describe the collection of representative water samples from monitoring wells, such as Gibb et al. (1981); Scalf et al. (1985); and EPA (1983, 1986). Multilevel monitoring wells, however, should be used in place of various depth well clusters wherever possible (Pickens et al., 1981).

The location of monitoring wells and frequency of sample collection depends on the site hydrogeology. Radionuclide detection monitoring will surely involve the use of monitoring wells. Nonradiological chemical analysis needs can be integrated into the detection monitoring procedures.

The role of monitoring wells may be slightly different at humid sites (shallower water table) than at arid sites (deeper water table). The water chemistry within the saturated zone at a humid site may be more representative of pore water chemistry within the engineered barriers than at arid sites because the water travels a shorter distance at humid sites. At sites with shallow ground water, chemical analysis of samples from monitoring wells may be used to infer final conditions of pore water after it has passed through the engineered barriers.

4.6.5.2 Suction-type Sampling Lysimeters. Suction-type sampling lysimeters, such as suction cup lysimeters, are commonly used to obtain pore water/gas samples under unsaturated conditions. A porous ceramic cup is mounted on the end of a tube and water from the surrounding media enters the cup using a vacuum applied at the surface end of the tube. Samples can not be withdrawn in dry soils (- 0.5 to 0.8 bar) or frozen soils. Variations are used that employ different vacuum delivery and sample withdrawal systems (Rhoades and Oster, 1986). Other variations use a filter candle in lieu of a suction cup (Rhoades and Oster, 1986).

Several factors severely limit the operation of suction-type devices (Everett et al., 1984; Everett and McMillion, 1985). These factors involve plugging of the porous segments of the lysimeters, soil tension operational ranges, adsorption onto and screening by the materials comprising the lysimeter parts, and loss of volatile fractions (such as CO_2) under negative pressures. Suction extraction of pore water causes substantial degassing of CO_2 and other important gases that are dissolved in the water (Suarez, 1986). Peters and Healy (1988) observed that even if samples can be withdrawn, the representativeness is questionable.

4.6.5.3 Sump Collection Lysimeters and Leachate Collection Systems. An alternative to suction-type lysimeters is gravity feed sump collection lysimeters (Fetter, 1988). Water collects in a designed depression of a synthetic geomembrane. The material above the geomembrane becomes saturated, forcing the water to flow to a wet well, where it can be sampled. Collection lysimeters are less prone to failure than suction-type lysimeters and have the added advantage that they can be made any size.

4.6.5.4 Soil Sampling Methods. Solid samples of unsaturated or saturated zones are obtained by hand or auger and transported to a laboratory. Normally, samples are taken in depth increments. Samples are often used to prepare a saturated extract that is then analyzed to determine the concentrations of specific constituents (Page, 1982). Direct sampling can provide very high quality results depending on the analysis procedures; however, many samples at many locations are necessary to provide data representative of a region. The methods can be used without relying on in situ sampling equipment, but samples can not be taken in the same location. Often times, spatial variability will preclude the comparison between successive samples. Use of direct soil sampling methods should be minimized throughout the disposal region because holes will degrade the barriers' performance. Some shallow sampling of the vegetative top cover may be acceptable if the hole can be refilled and the soil recompacted. Direct sampling is very labor intensive and expensive.

4.6.5.5 Salinity Sensors. Electrical resistivity of pore water can be estimated in situ with a buried electrical resistivity cell made from ceramic (Rhoades and Oster, 1986). The cell consists of two electrodes within a porous ceramic matrix. The sensor also includes a thermistor to measure temperature, so that the measured resistivity can be referenced to a standard temperature. Salinity sensors can provide automatic data acquisition to a common data logger.

The estimation assumes diffusional equilibrium between the ceramic solution and the pore water solution and constant ceramic water content as the surrounding soil wets and dries. Sensors have been made that remain saturated to negative water pressures of 20 bars (Rhoades and Oster, 1986).

Similar data cannot be obtained using soil samples because of changes caused by sample removal and dilution with water to obtain an extract. Although similar data can be obtained with suction-type and collection lysimeters, the use of salinity sensors permits measurement in drier materials. However, salinity sensors cannot provide the specific concentrations of chemical compounds. Similar data can be obtained using electrical and electromagnetic geophysical techniques, and the extremely location-specific data from salinity sensors can be effectively used to increase confidence in nonintrusive geophysical measurements.

4.6.5.6 Pore Gas Sampling. Surface flux boxes and buried probes can be used to collect pore gas samples (Anderson, 1982). Specific gases to monitor include H_2, CO_2, CH_4, and H_2S. Subsurface gas production can be inferred by their flux at the surface (nonintrusive) or sampled at depth using pore gas samplers (intrusive). A mix of both types is suggested. Pore gas sampling for monitoring performance of engineered barriers can be integrated into the radionuclide detection program as radionuclides can be released by venting through deteriorated containers (Kunz, 1982).

There are many examples of potential uses of pore gas analyses. Assuming that equilibrium is obtained for important compounds between the aqueous and gaseous phases, the analysis of pore air can be used to predict certain aspects of aqueous chemistry (Hem, 1985). Kunz (1982) observed that the amount of water seeping through a LLWDF is one of the most important factors that influence the concentrations of chemicals in the pore gas. Biological decomposition of organic materials (such as geosynthetics and waste byproducts) will produce CO_2 and CH_4 depending on the availability of oxygen (Bremner and Blackmer, 1982). Hydrogen sulfide gas is an indicator of redox conditions and anaerobic decomposition of organics. Hydrogen gas may be produced in detectable concentrations because of corrosion of reinforcements in concrete (MacKenzie et al., 1986). Geosynthetic membranes should impede pore gases from rising to the surface. Detection of such gases may indicate a hole through the geomembrane.

4.7 Subsurface Monitoring Using Geophysical Techniques

For the purposes of this report, the term geophysical technique is restricted to a certain type of geophysical method; specifically, geophysical monitoring techniques that input some type of energy (seismic, electromagnetic, nuclear) into a material and then measure the material's response.

4.7.1 Purpose. Several types of geophysical methods are ideally suited to measure the properties of a region for which it is impossible or impractical to gain direct access. Geophysical techniques are used to collect data that can be interpreted to provide bulk measurements of many important physical, chemical, and hydrologic conditions within the subsurface components. A suite of geophysical techniques could perform three primary functions as part of a LLWDF monitoring program:

1. Provide an estimate of the large-scale spatial variability.

2. Monitor changes in the spatial configuration of geophysical properties.

3. Periodically calibrate/confirm measurements from in situ instruments.

The interpretation can serve to indicate whether the component's response is uniform or whether there is some spatial variation that may not be detected by specific point measurements. Spatial variation in geophysical properties may lead to a qualified decision to increase numbers/locations of installed instruments.

If the variation can be attributed to a known and specific physical, chemical, or hydrologic condition, then geophysical techniques can be used to remotely monitor that condition. An example of "pure" measurements is neutron thermalization logging, which is predominantly a measurement of water content. In this case, geophysical monitoring may even provide more accurate data than are available from in situ instruments (such as heat dissipation sensors or electrical resistance blocks) and could be used to calibrate the in situ instruments (assuming the instrument is situated within the neutron probe's zone of influence).

Several geophysical properties respond to the amount of water in a porous media. The level of response is often high enough to be measured by geophysical techniques. For example, Sen et al. (1981) has shown that the relative dielectric permittivity of air, silica, and water are approximately 1, 4.5, and 80, respectively. Changes in the water content of a material should be detected by a high frequency radar system. (See Section 4.7.5 for further discussion of electromagnetic techniques.)

4.7.2 Location and Implementation. Geophysical methods can be categorized by the location of the instruments and by the geophysical properties that the instruments measure or respond to. Table 9 shows the geophysical techniques and modes of application that are considered as most appropriate in terms of the monitoring objectives.

Table 9. Application modes of geophysical techniques considered to best fulfill monitoring objectives.

Geophysical Property or Method	Surface	Hole-to-Hole Surface-to-Hole	Downhole
Seismic	X	X	
Electromagnetic			
High-frequency (radar)	X	X	X
Low-frequency (induction)	X	X	X
Resistivity	X	X	
Nuclear			
Neutron thermalization			X
Gamma attenuation		X	X

Surface geophysical techniques can be executed in a profile or sounding mode. Profile surveys are conducted by traversing a line (one dimension) or grid (two dimension) to determine horizontal variations in geophysical properties. Sounding surveys determine vertical variations (one dimension) in geophysical properties. Commonly, combinations of surface sounding and surface profiling surveys can be conducted resulting in a three-dimensional representation of the subsurface. Surface geophysical techniques require only minimal disturbance of vegetative top cover (walking or short probes into the top 20 to 30 cm).

Many of the geophysical techniques considered here are applicable to hole-to-hole (crosshole) or surface-to-hole surveys. This application of geophysical measurements uses a multiple of source and receiver locations to transect the area between the holes from as many angles as possible, thereby yielding a highly redundant sampling of the area. Auger holes can be placed outside the cover boundaries. Each geophysical test can employ a different arrangement of source and receiver locations; however, consistent arrangements allow for differencing as discussed in Section 3.7.4. Crosshole geophysical tests allow complete horizontal coverage beneath the vault without intrusion into sensitive regions.

Casing materials and dry holes can limit the usefulness of a downhole or crosshole geophysical technique. In general, resistivity measurements will not work in dry holes or in holes cased with conductive metals. Electromagnetic induction methods work in dry holes but will not work in holes cased with conductive metals. The hole diameter, type of casing tube material (PVC, aluminum, or stainless steel), and grout backfill can affect the sensitivity of the neutron probe measurements; however, most hole constructions could provide usable water content measurements (Keller et al., 1990). In summary, the compatibility of hole construction and geophysical technique should be considered.

4.7.3 Frequency. The frequency of subsurface monitoring depends on the specific objectives of each geophysical technique. All recharge events probably do not need to be monitored with geophysical techniques. A short-duration test may be useful to determine large-scale redistribution of infiltrated water.

4.7.4 Interpretation Considerations. Interpretations are often subjective, based on the experience of the geophysical interpreter. Sometimes interpretations are relatively straightforward, such as neutron thermalization counts for moisture content. But usually geophysical properties (wave velocity, attenuation, permittivity, and resistivity) depend on more than one physical, chemical, or hydrologic condition. Fortunately, much of this "nonuniqueness" can be resolved (made "unique") through the use of multiple geophysical techniques and other types of measurement techniques.

Because a LLWDF is constructed to known dimensions and locations, accurate models can be used to assist the interpretation. This is a luxury to geophysical interpreters who usually deal with much less spatial information.

Geophysical measurements using consistent instrument and detector locations over time can be subtracted from measurements taken at an earlier time in an interpretation process known as differencing. Asch and Morrison (1989) investigated the process of differencing specifically for monitoring changes in a waste repository such as a concrete vault. Differencing can also be very useful in diminishing the effects caused by surface changes in water content when the objective is to monitor water content within the vault or backfill surrounding the vault.

The reason that differencing is so useful for electrical surveys is that electric potential distribution near the surface is not affected by changes in the location of the source electrode if the source electrode is relatively far away. Thus, the differencing of apparent resistivities measured on the surface from two source positions at depth would be small in the absence of the deep feature (concrete vault). However, because the vault is relatively close to the buried electrodes, the pattern of potential distribution changes significantly for changes in source position. Differencing now accentuates the vault and other subsurface features.

Geophysical data resulting from crosshole or surface-to-hole surveys can benefit from specialized interpretation procedures. Inversion of the resulting data (generating a physical model from the measured data) is accomplished using reconstruction algorithms termed tomographic inversion. Crosshole and surface-to-hole resistivity surveys can be interpreted by inversion using surface-integral models (Asch and Morrison, 1989). Tomographic inversion routines serve to transform the area between the holes into a cellular space with each cell (pixel) having a characteristic value of wave propagation velocity or attenuation. Many tomographic inversion routines are available (Ivenson, 1983; Lo, 1988; Peterson et al., 1985; Pratt and Worthington, 1988). The choice of a particular inversion method depends mainly on the geophysical contrasts between the source and receiver; significant contrasts can be handled better using an inversion method that allows for wave diffraction.

4.7.5 Surface and Crosshole Electromagnetic Techniques. Electromagnetic (EM) techniques considered here include the low-frequency EM induction technique and higher-frequency radar methods. The low-frequency EM induction technique induces a current in the ground by an alternating low-frequency current (1 to 100 kHz) in a coil at the surface or in an auger hole. The changes in magnitude and phase of the individual current are measured by a receiver coil (McNeill, 1980). Alternatively, radar methods use a transmitting antenna that directs an EM pulse of 100-1000 MHz frequency into the ground and a receiving antenna that records either reflected pulse returns or transmitted pulse arrivals depending on where the receiving antenna is located. Two general categories of radar methods are briefly discussed: surface techniques (often termed ground penetrating radar or GPR) and techniques using below ground transmitting and/or receiving antennas.

Surface applications of EM methods do not compromise the performance of the cover. EM methods applied downhole or between holes require nonconductive (such as PVC) cased holes that could be located outside the cover boundary. Electromagnetic induction surveys are described by Benson (1984); McNeill (1980); Topp et al. (1980); Weber et al. (1984, 1985). Ground penetrating radar surveys are described by Daniels (1989) and Benson (1984). Crosshole electromagnetic surveys are described by Daily and Ramirez (1989) and Niva and Olsson (1987). Research in the field of EM methods is ongoing and rapidly advancing state of the art, especially for the crosshole tomographic applications.

The two principal electrical properties that affect the attenuation and propagation of EM waves are conductivity and dielectric permittivity. In general, conductivity is important for lower frequency waves (<1 MHz), while both the materials' dielectric permittivity and conductivity affect the higher frequency waves (>1 MHz). Dielectric permittivity is ignored for low-frequency EM induction methods (and galvanic resistivity methods) and both electrical properties affect the radar frequencies (Daniels, 1989).

EM methods can provide useful data representative of several physical, chemical, and hydrologic conditions that describe the status of engineered barriers over time. EM methods could potentially monitor

- Vertical movement and horizontal continuity of subsurface barriers
- Water content changes
- Changes in pore water electrolyte concentrations.

Interpretation of which of these conditions actually occurred may be difficult using EM methods alone. However, with additional determinate measurements of such conditions (e.g., from heat dissipation sensors and water samples from a lysimeter), changes measured using EM methods could be evaluated to provide unique information on the barriers' status.

When electrically conductive materials are used to construct engineered barriers, difficulties in the use of high frequency EM methods are created. For example, although strong GPR reflections will be caused by clay layers, they also have the effect of severely attenuating the signal beyond the clay. Fortunately, geosynthetics are often made of organic polymer plastics that are characteristically insulators and will not attenuate EM waves, but they will cause a reflection. Crosshole radar may overcome difficulties in "seeing through" electrically conductive clay if such clay can be avoided by transmitting and receiving EM waves through the sides of the disposal system beneath clay barriers. Lower frequency EM induction measurements are also well suited to crosshole surveys, up to 100 m, and are not limited by clay.

4.7.6 Surface and Crosshole Resistivity Techniques. Monitoring changes in water content (and to a lesser degree pore water salinity and clay content) is possible with integration of nonintrusive resistivity measurements with measurements of electrolyte chemistry and water content. Use of both conventional galvanic resistivity and induced polarization is helpful to differentiate the effects of water content, pore water salinity, and clay content.

Electrode arrays on the surface can provide high quality information on water content and redistribution in the upper 1 or 2 m of the cover as demonstrated by Kean et al. (1987). Parra (1988) and Parra and Owen (1988) modeled the electrical response of leaks beneath a geosynthetic membrane and gave leak scenarios that would be detectable from surface resistivity measurements.

Electrodes located in holes outside the cover boundary used in conjunction with surface arrays are more sensitive to relatively small resistivity changes in the vault and backfill than surface array alone. Asch and Morrison (1989) used a idealized model of a waste vault to demonstrate the effectiveness of resistivity monitoring with a combination of surface and subsurface electrodes. Downhole electrical logging is commonly practiced for hydrogeologic studies. Most downhole electric methods require a fluid-filled hole and may not be practical at many LLWDF sites.

The effectiveness of resistivity measurements is primarily due to the relationship between water-filled pores and bulk resistivity. However, the effectiveness of interpreting water content from bulk resistivity measurements is limited by the dependance of resistivity with pore water salinity and to a lesser degree, the dependance of resistivity with clay content. Most mineral grains are insulators, so electrical current must flow through pores filled with electrolyte solutions. The amount of water-filled pores and salinity of the pore fluid are simultaneously measured by conventional (galvanic) resistivity techniques. Clay enhances the apparent resistivity of the pore water (and thus bulk resistivity) through cation exchange reactions. The relationships are proposed by Vinegar and Waxman (1984) in a modification of the familiar Archie's equation.

$$\sigma_{bulk} = \sigma_{solution}\phi^{m} + \sigma_{clay} \quad (5)$$

where σ_{bulk} is complex bulk electrical conductivity (1/resistivity); $\sigma_{solution}$ is pore water conductivity; ϕ is porosity with exponent m usually close to 2; and σ_{clay} is complex conductivity of clay. Complex conductivities result from the redistribution of electrical charges on clay surfaces; this redistribution potential is only measurable using induced polarization (IP) techniques (Park and Dickey, 1989). Fortunately, instruments are available to measure both galvanic resistance and induced polarization using the same electrode arrays.

4.7.7 Surface and Crosshole Seismic Techniques. Seismic methods utilize the propagation of waves through materials. This propagation depends upon the material's elastic properties (Telford et al., 1976). In terms of LLWDF monitoring, physical properties such as bulk density, porosity, and water content affect seismic wave velocity and attenuation.

Uses of surface and crosshole seismic techniques are limited for the overall monitoring objectives because better geophysical methods exist to measure porosity and water content. However, seismic waves do not suffer the difficulties associated with clay as do electromagnetic methods. High resolution seismic reflection (Hunter et al., 1984; Knapp and Steeples, 1986) and crosshole seismic imaging (King and Witten, 1989) have great potential to monitor vertical movement and horizontal continuity of subsurface barriers and shallow water tables.

The application and technology of high-resolution reflection is rapidly evolving. Common-depth-point (Knapp and Steeples, 1986) and optimum offset (Hunter et al., 1984) are two seismic reflection data acquisition procedures that appear most promising. There remains a great deal of development and testing to perfect and understand the capabilities of seismic geotomography. However, the technology has reached a level where this research can be accomplished concurrently with the collection of needed data at actual survey sites (King and Witten, 1989).

4.7.8 Nuclear Logging Techniques

4.7.8.1 Neutron Thermalization. The neutron-thermalization method indirectly measures volumetric water content. A sonde (commonly called the neutron probe) is lowered through access tubing and bulk volumetric water content can be inferred to a radius of less than 10 cm in wet material to greater than 25 cm in dry material (Gardner, 1986). It is applicable above or below the water table but is generally used to measure moisture content within unsaturated materials. The method requires a minimum 5 cm access hole augered to the depth of interest.

This method is highly intrusive and use within the active disposal region should be minimized. With careful calibration to each soil or material type encountered, the standard error of the volumetric water content is ±1 to 5% (based on gravimetric analysis) (Gardner, 1986). Without adequate calibration or when calibration curves become questionable, only relative changes in moisture content between measurement intervals can be obtained.

The neutron-thermalization method involves the use of a fast-neutron emitting radioactive source and a detector and scaler to monitor slower moving or thermalized neutrons. The radioactive source is usually americium activated beryllium. The source and detector are located within the same sonde. The detector is connected by an electrical cable to the scaler, which remains on land surface. The collected data are usually in thermal neutrons detected per time (count rate).

Most soils exhibit a nearly linear relation between count rate and volumetric wetness (Hillel, 1980). Several calibration options are available.

- Calibration curves specific for each engineered component can be developed by gravimetrically measuring volumetric water content of discrete depth samples after the access hole is augered. If each engineered subsystem can be assumed to be relatively homogeneous soon after construction and if moisture content varies with depth within one component then a several point calibration curve is possible (Healy et al., 1986; Pittman, 1989).

- Because the cover is constructed under strict quality control measures, neutron probe calibration could be conducted using a bin filled and compacted with the same material to be used in actual cover.

- The ratio of the rate count to the standard count performed within the probe's protective shield can be both a calibration point and a standard reading (Pittman, 1989).

- Rate count when soil around the tube is fully saturated (as determined by tensiometers) (Healy et al., 1986).

Certain elements besides hydrogen exhibit a high adsorption capacity for slow neutrons (e.g., chloride, boron, or cadmium). Also, appreciable amounts of hydrogen are present in clay and organic matter. If chloride concentrations are greater than 1000 mg/kg or if clay and organic content changes significantly over time then calibration curves should be recalculated (Hillel, 1980).

4.7.8.2 Gamma Attenuation. Two types of gamma ray attenuation methods are applied to the measurement of water content. The transmission method (Gardner, 1986; Telford et al., 1976) requires two parallel holes installed at precise distances apart. A sonde with a gamma photon source (e.g., cesium-137) is lowered in one hole. A second sonde with a detector (e.g., sodium iodide scintillation crystal) is lowered at the same speed in the second hole. The degree to which a beam of monoenergetic gamma rays is attenuated depends on the bulk density and water content. Assuming that the bulk density remains constant, changes between readings reflect changes in water content. The transmission method can resolve depth-wise water content to within 2 to 3 cm. However, because of difficulties in installing precisely parallel holes, the method is limited in depth.

The scattering method (Gardner, 1986; Telford et al., 1976) uses a single sonde containing both the source and detector separated by a lead shield. Some of the gamma rays beamed into the surrounding media are absorbed. Those back-scattered rays are detected and counted. Again, assuming that the bulk density remains constant, changes between readings indicate changes in water content.

Overall, gamma attenuation methods provide an excellent alternative and check for neutron-thermalization methods because gamma rays respond to a different condition (i.e., density not hydrogen ions). Interferences include those that change the bulk density such as shrinking/swelling clays and compaction from differential settlement.

5. MONITORING WITH A REPRESENTATIVE TEST AREA

5.1 Generic Design

The concept of the representative test area originates from the conflict between the requirement for extensive monitoring of the engineered barriers' performance and the need to ensure that any monitoring will not adversely affect the isolation potential of the disposal facility. The concept of this performance monitoring feature is similar to the design verification facility proposed for a high-level radioactive waste repository (St. John et al., 1982).

A representative test area located immediately adjacent to the actual disposal facility should be constructed during waste disposal operations. A representative test area should include the following three features:

1. Scaled-down surrogate vault with nonhazardous materials inside and an overlying surrogate engineered cover.
2. Access trench with replaceable monitoring instruments and nondestructive testing.
3. Archival disposal unit with retrievable coupons (small removable samples) of concrete, geosynthetic materials, and simulated waste packages.

The access trench and archival disposal unit should be incorporated into the surrogate facility leaving other parts of the surrogate facility available for more routine monitoring. Because other differences between the representative test area and actual disposal region will exist, attempts should be made to ensure that the two regions are as alike as possible. Consequently, the location, materials, construction procedures, and timing of construction should be identical to that of the actual facility. Intensive sampling during construction of the actual disposal facility and the representative test facility is crucial to establish the relationship between an intensely monitored surrogate facility and the actual facility. Both commonalities and differences should be characterized during construction before environmental changes and different monitoring activities are realized.

The representative test area should also involve a region within the total site boundary but away from the disposal facility and any associated buildings. The fourth feature included in a generic representative test area is an

4. Undisturbed region not directly impacted by engineered facility or disposal activities (representative of natural or background conditions).

5.2 Purpose

The purpose of a representative test area is to perform the following functions:

- Provide information to infer the performance of the actual disposal facility
- Characterize natural temporal variability without impacts of engineered disposal
- Establish relationships between background conditions and actual disposal facility conditions as impacts of the facility on the environment
- Help quantify confidence levels in the actual monitoring program
- Calibrate and test monitoring techniques and instrumentation for use at actual facility
- Calibrate and test new monitoring techniques and instrumentation for eventual use at an actual facility
- Provide a location for conducting monitoring tests that can not be conducted at the actual disposal facility because the tests could compromise performance
- Provide data on concrete and geosynthetic performance that cannot be obtained at the actual disposal facility.

Any constraints on the intrusiveness of the monitoring techniques and instruments are imposed to increase the probability that surrogate measurements are representative of conditions at the actual disposal facility. Intrusive monitoring will not harm human health or the environment as is the case with the actual disposal facility.

5.3 Limitations

Difficulties should be expected in comparing the representative test area to the disposal facility. However, it is believed that location alone will cause the two data populations to be more similar than laboratory or computer simulations of actual conditions. It is believed that potential advantages outweigh the consequences of these difficulties. Even the worst case scenario, no significant correlation, will allow development of calibrated models of surrogate engineered barrier degradation (from retrievable coupons and monitoring results) with model results applied to conditions existing at actual facility. Establishing statistical relationships is discussed in Section 6.

5.4 Features of Representative Test Area

5.4.1 Monitoring Techniques Common to Actual Disposal Region. All monitoring instruments, equipment, and installation procedures employed at the actual disposal facility should be used at the representative test area. The purpose of monitoring with the same techniques is twofold. Besides using the data to determine conditions and performance of the surrogate engineered barriers, the monitoring equipment can be used to test the performance and failure rate of the instruments under similar conditions to that of the actual disposal facility.

5.4.2 Access Trench. A portion of the surrogate facility should be accessible to permit instrument replacement and nondestructive measurements of in situ conditions of engineered barriers. The conceptual design of such access trenches is described by Cahill (1982); Foster et al. (1984); and Laney et al. (1988).

5.4.3 Retrievable Coupons. Another portion of the surrogate facility should be available for periodic retrieval of small samples (coupons) made of geosynthetics and concrete. Before retrieval, these coupons should be installed to create the same conditions as the actual engineered barriers. After retrieval, the coupons can be analyzed at a laboratory and the results used to infer the performance of the actual engineered barriers. The degree to which inferences can be made depends on the representativeness determined by statistical analysis of monitoring data.

Studies using retrievable coupons permit analyses of the engineered barriers that are not possible using any other methods. For example, the effects of pore solution chemistry on the barriers can not be remotely detected until significant fouling has occurred. This fouling and the chemical environment causing the fouling can be addressed using retrievable coupons. However, there are serious limitations concerning the representativeness that must be resolved to permit optimal inferences to be made.

5.4.4 Region Characteristic of Natural or Background Conditions. Background monitoring is an integral part of an effective monitoring program. Detection monitoring programs require knowledge of background concentrations before the impacts of radioactive or hazardous waste units can be determined. Similarly, performance monitoring programs can benefit from a knowledge of background conditions, especially in terms of natural temporal variability under very similar meteorological conditions. Therefore, parameters such as pore water and gas chemistry should be monitored in regions hydraulically upgradient from a disposal facility and in other regions not directly impacted by disposal operations.

5.4.5 Special Features. Other features such as weighing and/or drainage lysimeters can be installed to collect data to more precisely calibrate water budget as described by Clapp et al. (1988) and Phillips et al. (1988).

6. ANALYTICAL APPROACH

Effective data analysis critically depends on five steps:

1. Planning for the analysis
2. Creating the data base
3. Data verification
4. Data validation
5. Analysis of data to answer the specific questions.

Step 1. Planning for the Analysis

Before the data are collected, the format for recording and storing the data should be determined. This should include the units of measurement and the number of significant figures to be recorded. With the format predetermined, the data can be collected more efficiently and accurately. The steps and procedures for creation and updating of the computer-based data base should also be planned.

Standard Operating Procedures (SOPs) for measuring, collecting, and recording the data should be developed and followed. Data Quality Objectives (DQOs) should also be determined. DQOs are the specific requirements for the accuracy, precision, completeness, comparability, and representativeness of the collected data and are intended to ensure that if the DQOs are met then the data will be of sufficient quality to be useful for its intended purpose. Quality Assurance and Quality Control (QA/QC) methods and SOP's have to be designed to ensure the DQOs are met. Some useful references for developing DQOs and QA/QC procedures are

- *Guidelines and Specifications for Preparing Quality Assurance Plans.* EPA, 1980.
- *Policy and Program Requirements to Implement the Quality Assurance Program.* EPA, 1984a.
- *The Development of Data Quality Objectives.* EPA, 1984b.
- *Guidance for Preparation of Combined Work/Quality Assurance Project Plans for Environmental Monitoring.* EPA, 1984c.

References specifically dealing with monitoring radioactive LLW sites are

- NUREG-1293, *Quality Assurance Guidance for Low-Level Radioactive Waste Disposal Facility.* Pittiglio, 1987.
- NUREG-1383, *Guidance on the Application of Quality Assurance for Characterizing a Low-Level Radioactive Waste Disposal Site.* Pittiglio et al., 1989.
- NUREG-1388, *Environmental Monitoring of Low-Level Radioactive Waste Disposal Facility.* Shum et al., 1989.

It is usually very beneficial and often necessary to run a pilot study to collect a small amount of representative data before the full-blown study is done. This allows one to eliminate unforeseen problems and gives an estimate of the variability of the data and the precision of the measurements so the DQOs and QA/QC plans can be better formed. These preliminary data are also helpful in determining the proper sampling frequency and times. Sometimes, it is possible to get useful information from previous studies of a similar nature.

The general methods for analyzing the data should also be planned before the full effort of collecting the data is undertaken. By planning, one can be sure that the effort is directed to collecting the required information and avoids collecting useless data. Again, a pilot study can help refine and narrow the analysis methods considered.

Step 2. Data Base Creation

Once data become available, it can be entered into computer data base. It is important to maintain a good system of traceability, documenting all changes and corrections to the data base. The original data recording forms should be stored in a safe place for reference.

Step 3. Data Verification

Data verification involves checking the data base to be certain that the data originally recorded in official forms, logbooks, etc., agrees with what is actually in the data base. This involves using techniques ranging from manual checks and double entry of the data to more complicated statistic techniques. The appropriate techniques depend on the type of data and the amount of data to be checked. Many of the validation techniques discussed in the next section can also be useful for verification. Verification also normally includes checking to ensure that SOPs and QA/QC methods were followed and that the DQOs were met. This involves using the QA/QC data (e.g. blanks and duplicate measurements) to ascertain the accuracy and precision of the data.

Step 4. Data Validation

The goal of validation is to check the data to identify outliers (unusual data points) and to ensure these points are valid measurements. Validation often overlaps with data verification. Validation also involves exploring the data to discover important facts about the data that may be useful for outlier detection (e.g., a strong relationship exists between two variables).

Validation can range from very simple checks (e.g., checking for any pH values over 14 or under zero) to more complicated techniques (e.g., multivariate analysis) depending on the nature of the data. Specific statistical tools and techniques that are often useful in data validation follow. Any known or theoretical relationships between variables (e.g., charge balances) can be used as filters to validate the data. Redundant variables can be compared to see if there are mismatches representing outliers. Distribution plots (such as frequency histograms, Box and Whisker plots) are a useful way of summarizing the data and are excellent validation tools. Frequency histograms indicate the frequency of a measurement falling within a specified range of values. Box and whisker plots are simple graphs that summarizes the data (see Figure 5). The box usually indicates the sample 25th and 75th percentiles. The interquartile range (IQR) is the length of the box. The central vertical lines, called whiskers, extend from the box to the farthest observation within 1.5 IQRs of the box. Other features of box and whisker plots are shown in Figure 5. For all variables that may be related, bivariate plots should be generated

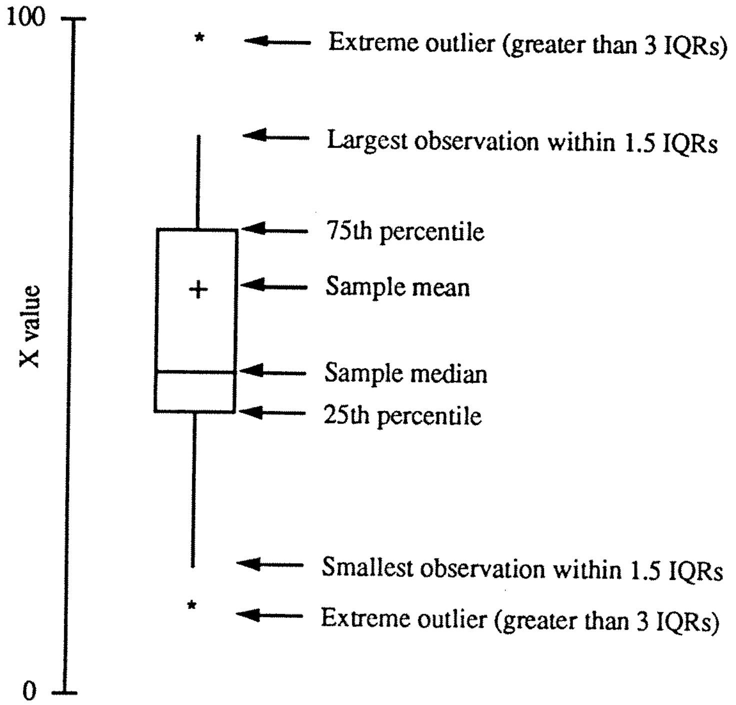

Figure 5. Box and whisker plot.

to quickly and easily assess the relationship and to check for obvious outliers. Outliers can also be found by doing a cluster analysis on related groups or suites of variables. Those clusters that have only one or two members can be considered outliers. By doing multiple regressions on suites of related variables, outliers can also be distinguished as points with large studentized residuals. The studentized residual is the ratio of the residual of an observation to the standard error of the residuals (Netter et. al., 1983). By removing these outliers and refitting the regression, more outliers may be found.

It should be noted that an outlier point should not be removed from the data base unless the point is found to be clearly in error. The fact that the point is unusual does not mean it should be discarded; it could represent very important true data.

If problems are found during verification or validation to which the end users should be alerted (e.g., a batch of samples did not meet DQOs or a data point is a suspect outlier) then a "tag" or "flag" variable can be used for this purpose. Once the data base has been verified and validated, it is ready for release to the general users.

Step 5. Analysis of Data to Answer Specific Questions

After the data has been validated, it can be analyzed to answer specific questions. This includes addressing questions that were raised as the purpose of the study. Often, there are additional questions and interests that are raised during the exploratory process of validation. Various statistical tools will be used depending on the specific question to be answered and the nature of the data.

The ultimate purpose of the LLWDF monitoring program is to ensure the facility is functioning as designed. Considerable thought needs to be given as to how to properly assess this, and the analysis should be planned before any data are collected. By thoughtful planning, one can ensure that all the necessary data are properly collected.

One general strategy for assessing that the facility is proper functioning over time is to assume that the facility was properly designed and constructed to start with and then to monitor for changes. Any significant change in measurements may indicate a change or impending change in the storage facility's ability to function properly. Statistical tools can be used to determine if a change in a measurement is significant and of real concern, or whether it is merely normal random variation. The measurements from the surrogate disposal unit and the background measurements will help assess the random variance component.

An important objective of a LLWDF monitoring program is to detect and characterize changes in conditions related to water movement. Trend detection and estimation is important because it describes the nature, magnitude, and rate of physical changes of the engineered barriers. Future performance can be evaluated in terms of acceptable baselines or acceptable projected changes-from-baselines that do not compromise the functions of the engineered barriers. Trends can be temporal and/or spatial.

Temporal trend detection is accomplished through several statistical methods ranging from simple graphic time plots through more general ANalysis Of VAriance (ANOVA) or regression techniques to complicated time-series analysis.

Spatial trends are analyzed with geostatistical techniques. Where temporal trends exist only in one dimension (time), variations in field parameters tend to be correlated over space in two or even three dimensions: laterally, longitudinally, and altitudinally. Similar to time-series analysis, geostatistical techniques operate on the premise that values for a variable at an unmeasured location can be estimated using correlated measurements taken nearby.

There are three distinct populations that will be monitored: the actual disposal facility, the surrogate facility, and the natural background population.

Two very important uses of monitoring the background and surrogate populations are assessing the "normal" conditions (i.e., conditions unimpacted by construction or storage) and assessing what the normal random variability is for different variables.

The surrogate facility can also be used to investigate relationships between very intrusive, very accurate measurement techniques (the kind possible only at the surrogate facility) and the less intrusive and less accurate measurements that one is forced to use at the actual disposal facility. Once these relationships are developed at the surrogate facility, they can be used to better understand the data from the actual disposal unit and determine the quality of the nonintrusive measurement techniques. Perhaps even predictive models can be developed at the surrogate facility so those variables that cannot be nonintrusively measured can be predicted from other nonintrusively measured variables.

The most obvious use of the surrogate archival trench is taking intrusive measurements representative of conditions in the actual disposal unit. Assessing the representativeness and comparability of the data is difficult and involves analyzing of the correlation between variables that can be measured at both sites and the correlation between these variables and the surrogate-measured-only variables. This is complicated and represents a major area of work that could yield useful results.

Another one of the uses of the three different populations is to provide checks and comparisons on data from other populations. For example, the pH measurements from both the actual disposal facility and the background will probably change some from day-to-day and from measurement-to-measurement. With only measurements from the actual facility available, if a real pH change occurred (i.e., a nonrandom change), it would have to be large to be detected. But if it turned out that the actual facility's pH and the background pH covaried together, and if a real change occurred that was due to or in association to the actual facility, this would be more easily detected because suddenly the pH values from the two populations would deviate.

7. SUMMARY AND CONCLUSIONS

This document is summarized by an explanation of the monitoring program implementation procedures. Three fundamental conclusions are presented, and the associated implications are suggested.

7.1 Implementation of Monitoring Program

This section is intended to guide those who will implement performance monitoring programs at LLWDFs. The explanation of the implementation process provides a summary of the document results and refers back to preceding sections where appropriate. Four major steps outline the implementation of the monitoring program.

1. Develop Conceptual Model of Facility and Environment

A conceptual model describes links among the facility performance objectives, the physical state of the facility, and human and natural causes of change. The resultant understanding should permit testable questions to be clearly stated and ultimately evaluated. The following three substeps provide the basis for the conceptual model.

A. Define site characteristics and specific facility design. The monitoring program should be based upon (a) site-specific conditions before facility construction commences and (b) the LLWDF design. As stated earlier, a monitoring program must develop from an effective, quality-assured, and documented site characterization. Site-specific information on meteorology and climatology, geology and seismology, hydrology, geochemical characteristics, geotechnical characteristics, and biotic features must be incorporated into the monitoring program. Materials used for each barrier should be characterized before, during, and after barrier construction. In this sense, facility characterization is an ongoing process throughout the operational phase.

B. Predict the processes that control water movement. Before developing a monitoring program, one or more working models must be identified that describe the processes likely to control behavior. The models must be based on a comprehensive knowledge of site and facility conditions as described in substep A. Physical models (i.e., Darcy's law and the water budget equation) and degradation mechanisms (i.e., erosion, biological intrusion, differential settlement, and chemical attack of concrete) have been identified as the models or descriptions of processes that control water movement. Given a particular geographic location and a specific facility design, the degradation mechanisms in Section 4 should be evaluated in terms of likelihood of occurrence and potential for barrier-specific damage.

C. Define the manner in which water movement affects performance of the facility. Enhanced water movement may affect performance in different ways for each facility design. Modeling should be conducted to estimate water movement levels and/or patterns that could become responsible for radionuclide release. Damage from degradation mechanisms should then be modeled with respect to its impact on water movement. From the mathematical performance modeling, action levels should be quantified for each physical, chemical, and hydraulic condition. Changes that exceed these predetermined action levels usually indicate the need for remedial action. Action levels may be in terms of absolute magnitude or in terms of rate of change.

2. Define Objectives of Monitoring Program

The ability of a LLWDF to isolate waste from the surrounding environment is highly dependent upon the performance of the barriers engineered around the waste. Seepage patterns and rates are important indicators of performance. Thus, the overall objective of the monitoring program is to quantify spatial and temporal water movement throughout the facility.

Every technique used in a monitoring program should be selected and implemented to assist in answering a specific question. A list of important hydrological questions or concerns should be developed. These questions should then be related to waste release scenarios. The goal of this step is to narrow the focus of monitoring from the vast number of questions and parameters that could be examined to those that will produce the necessary performance information.

There are no simple guidelines for producing specific questions to be answered. The questions should serve to identify specific potential impacts of water movement on specific barriers at specific times. To be useful, testable questions need not be complex. Healy et al. (1986) studied the trench covers of a LLWDF in an attempt to define the amount, timing, and location of water movement into the trenches. Their concern led to the question, "What amount and application rate of precipitation leads to seepage through the trenches?" To answer this question, they monitored precipitation, evapotranspiration, surface runoff, and water storage within the trench cover.

3. Develop Monitoring Design

Step 3 uses the information produced in Steps 1 and 2 to develop a monitoring design that states what variables will be measured, what measurement techniques and instrumentation will be used, and where and when the measurements will be taken. A flowchart for developing a monitoring design is presented in Figure 6.

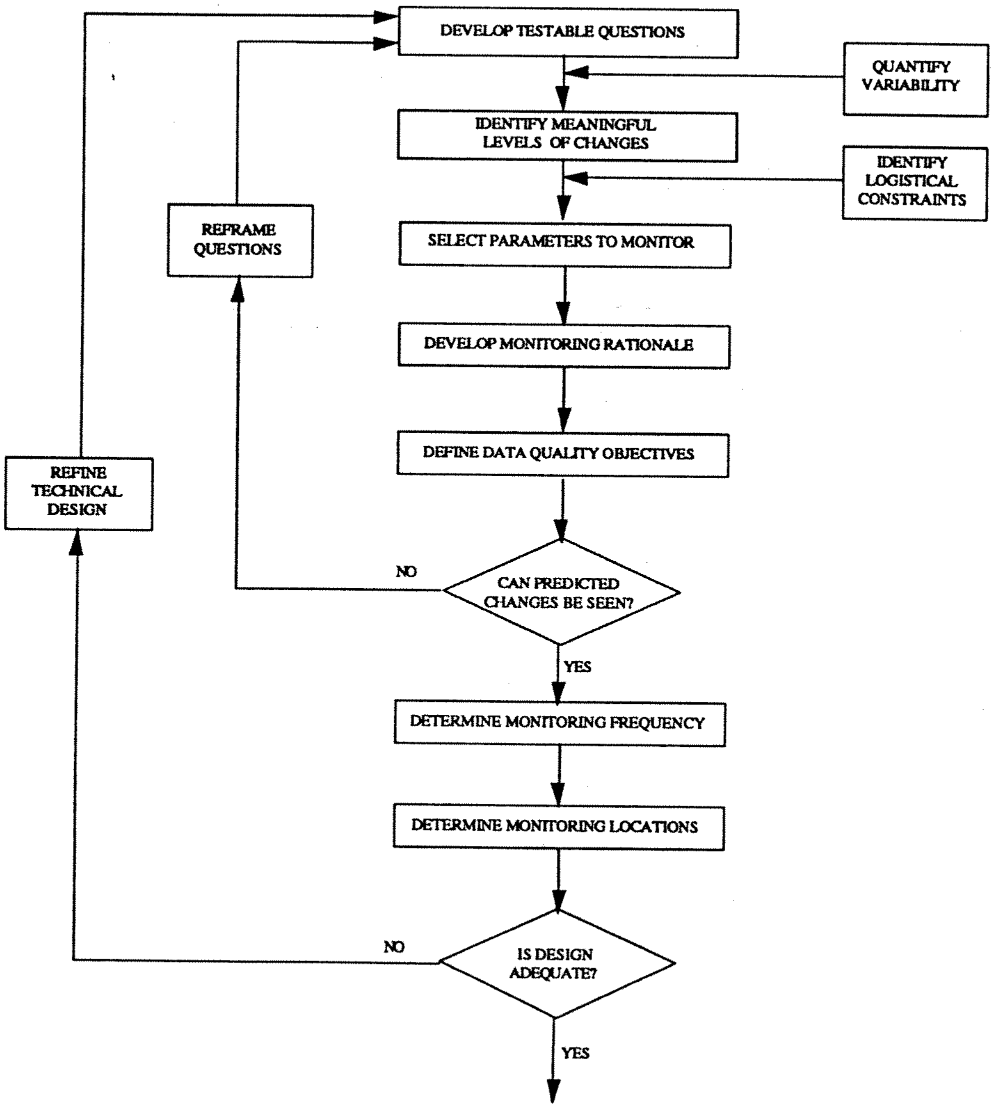

Figure 6. Flowchart for development of monitoring design (modified from National Research Council, 1990).

Meaningful levels of change should be identified. All kinds and levels of change are not equally important. The definition of a meaningful change is based on the manner in which water movement affects performance of the facility as determined in Step 1 and the testable questions developed in Step 2.

Identifying meaningful levels of change and variability will aid in selecting techniques and instrumentation. By estimating the maximum meaningful value of a parameter, the necessary range of an instrument's ability to obtain quality data is known. Similarly, the minimum meaningful value can predict the needed accuracy or sensitivity of monitoring methods. Further, natural variability creates a background of change that may make it difficult to quantify physical changes in the LLWDF. Thus, defining meaningful change depends in part on identifying and accounting for all sources of variability.

Logistical monitoring constraints at LLWDFs have been discussed throughout this document. In summary, intrusion through the barriers must be minimized to maintain control of water movement and maintain barrier stability; the facility should be designed and constructed to be monitored; and selected monitoring techniques should be suited to provide only necessary data and to perform well over the long-term.

The parameters describing water movement were identified in Section 3. It was determined that three interrelated categories of data should be collected to assess the barrier performance in terms of controlling water movement. Four hydrologic characteristics are necessary to quantify parameters directly related to water movement: energy levels, water content, hydraulic properties, and recharge conditions. Those parameters related to degradation mechanisms were identified after examining the types of damage that may result.

Given a set of parameters to be measured, a preliminary selection of monitoring techniques and instrumentation should be made. The demand to maintain integrity of the engineered barriers, minimize costs, and work with the limited capabilities of monitoring technologies suggests a monitoring rationale consisting of three approaches: intrusive measurements, nonintrusive (remote) measurements, and measurements at a representative test area (Section 2). Potentially useful monitoring techniques and instrumentation were presented in Section 4.

After evaluating a monitoring scheme for a certain site and facility design, specific DQOs should be developed. DQOs are part of an overall quality assurance program. Established quality control measures should support DQOs. Well-defined quality objectives ensure that the data collected are of adequate quality given the monitoring objectives and specific questions to be tested. The quality of decisions concerning facility closure is dependant upon the quality of the monitoring data. The highest quality data are accurate, precise, complete, comparable, and representative (EPA, 1987). The DQOs should then be assessed in terms of testable questions. If the questions cannot be resolved, then the questions should be reframed and/or DQOs redeveloped.

With specific DQOs clearly stated, the monitoring locations and frequencies can be determined. Important design aspects are presented for specific techniques and instrumentation in Sections 4 and 5. When data collection protocols are established, the likelihood of a adequate physical interpretation can be assessed. An adequate interpretation must answer the established hydrological questions.

4. Convert Data Into Useful Information

The raw data collected in a monitoring program usually do not directly address the information needs of decision makers. Data are individual facts, and information is data that have been processed, synthesized, and organized for a specific purpose (National Research Council, 1990).

Guidelines for data management and analysis were developed in Section 6. Data should be statistically and logically managed to build a data set with known confidence levels. Many statistical techniques are available to evaluate and analyze the data. An integrated statistical approach including multivariate analysis techniques is suggested.

An implemented monitoring program has three potential uses in evaluating the performance of the engineered barriers. These ongoing uses are

1. Establishing temporal baselines and spatial patterns. The monitoring data collected may be used to establish temporal baselines. Such baselines are developed using temporal analysis techniques, specifically trend detection and estimation. Temporal baselines may be

different for different areas of the facility. Thus, spatial pattern recognition will be coupled with established temporal baselines. Once baselines are established, deviations from the baseline may signal that corrective measures should be evaluated for the area specified.

2. Providing input to models. As discussed in Section 3, much of the data can be input to mathematical models that can further evaluate and predict the performance of the facility. The validity of models can increase when degrees of confidence and/or variance can be assigned to data input to the model.

3. Evaluating and modifying monitoring operations. The physical state of the facility will probably change and consequently the monitoring program should adapt to a changing environment. The monitoring program should evolve to increase cost-effectiveness and confidence levels by changing measurement technique, location, and/or frequency.

7.2 Conclusions and Recommendations

A generic design of a monitoring program was developed to assess physical changes in LLWDFs. Monitoring data can be used to evaluate current and future performance of the facility. These performance evaluations will ensure that closure decisions are based on scientifically valid and statistically significant interpretations. Three fundamental conclusions are drawn based on the evaluation of a generic monitoring program design. Further research is recommended in support of these conclusions

Performance of engineered barriers depends on their physical state. Performance of LLWDFs is based on radioactive dose levels and long-term site stability. Barriers constructed around the waste will perform satisfactorily if they limit release of radioactivity and remain structurally stable. Assuming that adequate barriers are constructed, the barriers must change (physically, chemically, or hydraulically) for facility performance to be compromised. In effect, if the physical, chemical, and hydraulic conditions of a barrier are known then performance can be predicted.

Work is needed to further develop the relationships between barrier performance and the barrier's physical, chemical, and hydraulic conditions. Meaningful changes should be evaluated and quantified.

Both intrusive and nonintrusive techniques should be employed. Monitoring activities at a waste disposal facility must not compromise performance. The use of intrusive techniques should be limited at the actual disposal units. In situ conditions at actual disposal units can be monitored without degrading the integrity of the barriers by using remote or nonintrusive techniques.

Work is needed to further develop the relationship between measurements from intrusive and nonintrusive techniques. If nonintrusive measurements prove to be indicative of specific conditions within the facility then intrusive measurements can be reduced in frequency and location.

Integration of data sets from three monitoring regions is necessary to define true physical state of engineered barriers. Measurement variability originates from several different sources. Integration of redundant data from the actual facility, the surrogate facility, and an undisturbed region can remove natural and instrument variability from true physical changes.

Further work is needed to develop the statistical evaluation plan. Field data from each of the three monitoring regions could be collected and analyzed for correlations between data sets. Field data could be collected at an existing LLW disposal site, an existing test site, or a newly constructed test site.

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11. ABSTRACT *(200 words or less)*

Part I of this report describes and evaluates potential impacts associated with changes in environmental conditions on a low-level radioactive waste disposal site over a long period of time.

Part II of this report contains guidance on the design and implementation of a performance monitoring program for low-level radioactive waste disposal facilities.

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