NUREG/CR-5858
PNL-7986

Information for Consideration in Reviewing Groundwater Protection Plans for Uranium Mill Tailings Sites

[illegible]

[illegible] Northwest Laboratory
[illegible]
[illegible] Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

NUREG/CR-5858
PNL-7986

Information for Consideration in Reviewing Groundwater Protection Plans for Uranium Mill Tailings Sites

Manuscript Completed: March 1992
Date Published: May 1992

Prepared by
P. D. Thorne

Pacific Northwest Laboratory
Richland, WA 99352

Prepared for
Division of Low-Level Waste Management and Decommissioning
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN L1411

Abstract

Guidelines and acceptance criteria were developed for reviewing certain aspects of groundwater protection plans for uranium mill tailings sites. The aspects covered include 1) leaching and long-term releases of hazardous and radioactive constituents from tailings and other contaminated materials, 2) attenuation of hazardous and radioactive constituents in groundwater under saturated and unsaturated conditions, 3) design and implementation of groundwater monitoring programs, 4) design and construction of groundwater protection barriers, and 5) efficiency and effectiveness of groundwater cleanup programs. The objective of these guidelines is to assist the U.S. Nuclear Regulatory Commission staff in reviewing Remedial Action Plans for inactive waste sites and licensing application documents for active commercial uranium and thorium mills.

Contents

Executive Summary

The Uranium Mill Tailings Radiation Control Act (UMTRCA) mandates protection of groundwater resources at sites associated with the milling of uranium and thorium ores. Title I of this act established the Uranium Mill Tailings Remedial Action Program and made the U.S. Department of Energy responsible for control of residual waste materials and cleanup of contamination at several specified inactive processing sites. Title II requires control of wastes at other commercial uranium and thorium processing sites. Under UMTRCA, the U.S. Nuclear Regulatory Commission (NRC) must ensure that waste disposal and cleanup plans for both Title I and Title II sites meet applicable standards for groundwater protection.

Guidelines and acceptance criteria were developed for use by NRC staff in reviewing certain aspects of groundwater protection plans for uranium processing sites. The aspects of groundwater protection covered in this report are 1) leaching and long-term releases of hazardous and radioactive constituents from tailings and other contaminated materials, 2) attenuation of hazardous and radioactive constituents in groundwater under saturated and unsaturated conditions, 3) design and implementation of groundwater monitoring programs, 4) design and construction of groundwater protection barriers, and 5) efficiency and effectiveness of groundwater cleanup programs. The guidelines and acceptance criteria are based on U.S. Environmental Protection Agency (EPA) standards in 40 CFR Part 192 and on NRC licensing requirements in 10 CFR Part 40 Appendix A. The EPA standards for inactive, Title I sites are not yet final and are subject to change.

Disposal facilities must be designed to meet a site-specific groundwater protection standard. In most cases, it must be demonstrated that the facility design, together with natural site conditions, will not result in specified hazardous constituents reaching the "point of compliance" in the uppermost aquifer for 1000 years. Both the long-term seepage rate through the facility and the concentrations of hazardous constituents in seepage must be determined. Uncertainty is introduced into the determination of seepage rate by factors including assumptions in operating conditions (i.e., saturated or unsaturated flow), representativeness of samples, and reliability of test methods. Additional uncertainty is inherent in predicting the concentrations of hazardous constituents in seepage. Acceptance criteria were developed to ensure that reliable methods and conservative assumptions are used in predicting long-term releases from the facility.

Guidelines and acceptance criteria were also developed for reviewing attenuation processes applied in performance assessments of uranium mill tailings sites. Hazardous constituents released from contaminated materials would be transported by seepage through the unsaturated zone and, subsequently, by groundwater flow in the saturated zone. During transport, physical and geochemical processes could contribute to the reduction of constituent concentrations. Physical processes that may reduce constituent concentrations in groundwater include dilution and radioactive decay. Geochemical processes include precipitation, co-precipitation, and adsorption. These processes may be used in the performance assessment of the disposal unit design to show that concentration limits at the point of compliance will be met for the design life of the facility.

Groundwater monitoring programs are required at uranium mill tailings sites to establish baseline conditions, allow detection of released hazardous constituents in the uppermost aquifer, ensure that groundwater protection standards are met, and evaluate the effectiveness of any required corrective actions. Baseline monitoring requires that adequate hydrogeologic information be provided concerning the soil and geologic formations underlying the proposed disposal site. The detection monitoring program is designed to detect leakage of hazardous constituents and provide data on background concentrations. Compliance monitoring must ensure that any statistically significant exceedence of concentration limits at the point of compliance is detected. The need for remedial action can then be identified. Acceptance criteria were developed for reviewing plans for these various types of groundwater monitoring.

Guidelines were also developed for reviewing the use of physical and geochemical barriers for groundwater protection. Liners are required for waste impoundments at some sites. Other types of physical or geochemical barriers may also be useful in the protection of groundwater resources. Physical barriers act to impede the flow of seepage or groundwater. Geochemical barriers consist of material placed in the flow path of contaminants that will react with and immobilize hazardous and radioactive constituents.

At some processing sites, existing groundwater contamination must be cleaned up. Review guidelines are given regarding the efficiency and effectiveness of various approaches to cleanup of contaminated groundwater. In many cases, the cleanup of groundwater at Title I sites has been deferred until final regulations are promulgated. If cleanup is deferred, it must be demonstrated that any planned disposal activities can proceed independently of groundwater cleanup and that public health and safety will not be endangered. Possible cleanup approaches include pump-and-treat, in situ treatment, and natural flushing. Regardless of the approach, cleanup goals must be established and the effectiveness of the proposed methods must be demonstrated with consideration of the uncertainties involved. Provisions must also be made for monitoring the effectiveness of the cleanup effort.

Introduction

The U.S. Nuclear Regulatory Commission (NRC) is responsible for concurring with plans for tailings disposal and for cleanup of existing contamination at several inactive uranium processing sites where remedial actions are being implemented by the U.S. Department of Energy (DOE). The NRC must also approve tailings disposal and cleanup plans for commercial uranium and thorium processing sites as part of its licensing responsibility. Protection of groundwater resources is an important aspect of such plans.

This report provides guidelines and acceptance criteria for reviewing certain aspects of groundwater protection plans for uranium mill tailings sites. The aspects covered include 1) leaching and long-term releases of hazardous and radioactive constituents from tailings and other contaminated materials, 2) attenuation of hazardous and radioactive constituents in groundwater under saturated and unsaturated conditions, 3) design and implementation of groundwater monitoring programs, 4) design and construction of groundwater protection barriers, and 5) efficiency and effectiveness of groundwater cleanup programs.

Review guidelines and acceptance criteria provided in this report will be used to update the NRC's Standard Review Plan for uranium mill tailings sites. The report will also provide technical guidance to NRC staff in reviewing Remedial Action Plans, Surveillance and Maintenance Plans, Alternative Concentration Limit Applications, Groundwater Cleanup Plans, license amendment support documents, and other licensing documents. The acceptance criteria are firm in that they are based on the current regulations. However, the regulations are designed to give the flexibility needed to achieve optimum results on a site-specific basis. In many cases, exceptions and alternatives are allowed as long as it can be shown that the level of protection for public health, safety, and the environment is equivalent or better than that which would be achieved under the regulations. A summary listing of all the identified acceptance criteria is provided in the appendix.

Regulatory Framework

In 1978 Congress passed the Uranium Mill Tailings Radiation Control Act (UMTRCA) to "provide for stabilization, disposal, and control in a safe and environmentally sound manner of such tailings in order to prevent or minimize radon diffusion into the environment...and other environmental hazards from such tailings." Title I of this act created the Uranium Mill Tailings Remedial Action Program (UMTRAP) and makes DOE responsible for control and cleanup of contamination at several specified inactive uranium processing sites. Title II of UMTRCA mandated the regulation of mill tailings at active uranium and thorium processing sites, including new sites and those operating at the time of the act. Several of these "active" sites have ceased operations since 1978. However, they still are regulated under Title II of UMTRCA.

UMTRCA directed the U.S. Environmental Protection Agency (EPA) to promulgate standards for both active and inactive uranium mill tailings sites for the protection of public health, safety, and the environment. The NRC is responsible for ensuring that these standards are met. For Title I sites, DOE must receive concurrence from NRC in the selection of a remedial action plan, performance of the remedial action, and closure of the site. The NRC also has the responsibility for licensing DOE or another agency to perform long-term surveillance and monitoring following completion of the remedial action. Under Title II, NRC is responsible for licensing and inspecting the operations of active uranium and thorium mills. The NRC terminates the operating license upon reclamation of the site, and licenses either DOE or the appropriate state to provide long-term surveillance and monitoring.

Title I Groundwater Protection Standards

The EPA standards pertaining to inactive processing sites were promulgated in 40 CFR Part 192 Subparts A-C with an effective date of March 7, 1983. Subpart A was directed at the stabilization and control of tailings. Subpart B covered cleanup of existing contamination. Subpart C provided guidance for implementation, including protection and cleanup of contaminated groundwater beneath and in the vicinity of inactive uranium processing sites. However, as a result of a court challenge, standards pertaining to groundwater protection at Title I sites [40 CFR 192.20(a)(2-3)] were remanded to EPA by the Tenth Circuit Court of Appeals on September 3, 1985. EPA was directed by the court "...to treat these toxic chemicals that pose a groundwater risk as it did in the active mill site regulations." On September 24, 1987, EPA published proposed groundwater standards (FR 36000) for Title I sites to replace those remanded. Until the final standards are promulgated, DOE is required to implement the proposed standards. The references to 40 CFR Part 192 in this report are to the proposed standards published on September 24, 1987.

DOE is responsible for implementing remedial actions at the Title I sites that will meet the EPA standards. The objective of DOE's Uranium Mill Tailings Remedial Action Program (UMTRAP) is to provide long-term closure of the inactive processing which will ensure low-maintenance requirements, isolation from intrusion, and minimal impact to human health and the environment. The design of each disposal facility is based on site-specific performance standards for 1) stabilization of the residual radioactive materials, and 2) cleanup of existing contamination.

Standards for Stabilization and Control of Residual Radioactive Materials

At each of the inactive Title I processing sites, DOE must design a disposal facility for the residual contaminated materials and demonstrate that the design will meet EPA's proposed groundwater protection standard in 40 CFR 192.02. This standard requires that the control for residual radioactive materials be designed to meet site-specific groundwater protection provisions previously established by EPA under the Resource Conservation and Recovery Act (RCRA). The RCRA regulations in 40 CFR 264.92-264.95 and 264.111(a-b) were applied to Title I sites with the addition of $^{226/228}$Ra, $^{234/238}$U, nitrate, molybdenum, and gross alpha activity to the table of constituent concentration limits. Administrative differences were specified that make DOE responsible for site characterization and cleanup activities. NRC is made responsible for facility permits in lieu of the EPA Regional Administrator. The RCRA requirement for liners and many other specific RCRA requirements for groundwater monitoring and corrective actions were not applied to the Title I sites.

To demonstrate that the proposed design meets groundwater protection standards, NRC (1988) requires that DOE 1) establish a site groundwater performance standard, 2) conduct a performance assessment, 3) demonstrate compliance with the closure performance standard, and 4) establish monitoring and corrective action programs.

The site groundwater standard (40 CFR 264.93-264.95) consists of a list of hazardous constituents, a corresponding list of concentration limits, and a point of compliance. The disposal facility must be designed so that hazardous constituents will not reach the point of compliance at concentrations higher than the specified limits within a defined 200- to 1000-year control period. Although 40 CFR 264.92 provides for establishment of the groundwater protection standard after hazardous constituents have entered the groundwater, the NRC staff considers that the standard should be established before design and construction of the disposal facility (NRC 1988). Otherwise, it would be difficult to design the disposal facility to meet the standard as required in 40 CFR 192(a)(3).

The list of hazardous constituents for each particular Title I site will be specified in the NRC's Technical Evaluation Report based on information provided by DOE in the Remedial Action Plan (NRC 1989). Potential hazardous constituents are those constituents listed in Appendix VIII of 40 CFR Part 261, or added in 40 CFR Part 192 (i.e., molybdenum, radium, uranium, or nitrate), which are reasonably expected to be in or derived from the contaminated materials.

The concentration limit for each hazardous constituent is based on the background concentration in groundwater at the site, a concentration limit specified in the regulations, or an approved alternate concentration limit. Factors to be considered in establishing an alternate concentration limit are listed in 40 CFR 264.94(b). An alternate concentration limit may be established for a hazardous constituent if the NRC finds that the constituent will not pose a substantial present or potential hazard to human health or the environment as long as the alternate concentration limit is not exceeded and that the alternate concentration limit is as low as reasonably achievable considering practicable corrective actions that could be implemented to improve the performance of the disposal facility.

The third component of the site-specific groundwater standard is a point of compliance (40 CFR 264.95), which will also be specified in NRC's Technical Evaluation Report based on information provided by DOE in the Remedial Action Plan. The point of compliance is actually a surface at the downgradient edge of the "waste management area" and extending downward through the uppermost aquifer. The waste management area is defined as the area on which waste will be placed along with the area taken up by dikes or other containment structures. Because the point of compliance extends down into the uppermost aquifer, it also applies to any perched groundwater zones that might develop above the uppermost aquifer. Detection monitoring must be conducted at the point of compliance.

DOE's performance assessment must demonstrate that the disposal design, together with natural site conditions, will result in the concentrations of potential hazardous constituents at the point of compliance remaining lower than the established concentration limits during the designed control period. The control period must be 1000 years, to the extent "reasonably achievable", and, in any case, at least 200 years. To satisfy the closure performance standard, DOE must show that the disposal design will comply with the groundwater protection standard for this control period and that it does not rely on maintenance to ensure continued compliance. Monitoring of hazardous constituents in groundwater is required to establish background concentrations and to demonstrate that initial performance of the disposal facility conforms with the design to meet groundwater protection and closure standards. It is not intended that monitoring be continued for the entire 200- to 1000-year designed control period of the facility.

Standards for Cleanup of Existing Groundwater Contamination

In addition to safe disposal of residual radioactive materials at Title I sites, UMTRCA mandates the remediation of residual contamination, including contaminated groundwater, to the extent necessary to protect human health and safety, and the environment.

To date, cleanup of existing contaminated groundwater at nearly all of the abandoned processing sites has been deferred by DOE until final groundwater protection standards are promulgated by EPA. NRC has been willing to accept this deferral and give conditional concurrence to remedial actions for disposal of residual contaminated materials (tailings) if DOE demonstrates that human health is not endangered by contaminated groundwater and the disposal activities will not prejudice or preclude future groundwater remediation.

EPA's proposed standard for cleanup of groundwater contamination requires that the concentrations of constituents that have been released from the residual radioactive material and are listed in 40 CFR 264.93 or 40 CFR 192.01 not exceed the higher of 1) the background concentration in groundwater, 2) the listed maximum concentration limit, or 3) an approved alternate concentration limit. This cleanup standard is nearly the same as the standard for groundwater protection at disposal sites, the main difference being the lack of a point of compliance for groundwater cleanup. Any water in the saturated zone that contains hazardous or radioactive constituents above the applicable concentration limits would require restoration to meet the cleanup standard or supplemental standards, if applicable.

The definition of groundwater given in 40 CFR 192.01(j) of the proposed regulations is worded so that water in the unsaturated zone would not be considered groundwater. Therefore, the cleanup requirement does not apply to contaminated water held in pore spaces in the unsaturated zone. However, if there is a potential for water in the unsaturated zone to migrate downward and contaminate groundwater in the future, it would be prudent to consider this source of contaminants in the cleanup program.

Implementation of groundwater cleanup is addressed by 40 CFR 192.20(b)(4). This section states that the Remedial Action Plan should include the schedule and steps necessary to complete groundwater cleanup. It also specifies that hazardous and radioactive constituents in groundwater should be identified and the extent of contamination determined. Future movement of contaminants and the effects of attenuation processes should be predicted. 40 CFR 192.12(4) provides the option for extending the remedial period if certain criteria are met. If the remedial period is extended, 40 CFR 192.20(4) requires that a monitoring program should be provided to verify the movement and attenuation of contaminants.

Supplemental Standards

Supplemental standards for Title I sites are given in 40 CFR 192.22. The supplemental standards may be applied to stabilization of tailings or cleanup of groundwater contamination if one of the following conditions exists.

- The required remedial actions for disposal or cleanup would pose a clear and present risk of injury to workers or members of the public that cannot be avoided or reduced by reasonable measures.
- The required remedial actions for cleanup of land or groundwater, or the acquisition of materials for tailings stabilization, would produce environmental harm that is clearly excessive compared to the health benefits to persons living on or near the site now or in the future.
- There is no known remedial action.
- Restoration of groundwater quality is technically impracticable from an engineering perspective.
- The groundwater is Class III.

The supplemental standards state that remedial actions must come as close to meeting the otherwise applicable standards as is reasonable under the circumstances. If supplemental standards are applied to groundwater cleanup because restoration is technically impracticable or because the groundwater is Class III, remedial actions for groundwater restoration must be applied to ensure protection of human health and the environment at a minimum.

A different supplemental standard must be applied at a site if radionuclides other than ^{226}Ra and its decay products are "present in sufficient quantity and concentration to constitute a significant radiation hazard from the residual radioactive materials." This supplemental standard states that, in addition to the normal standards for stabilization of tailings and cleanup of existing contamination, the remedial actions must reduce the other radioactivity to levels that are as low as reasonably achievable.

Title II Groundwater Protection Standards

Subparts D and E of 40 CFR Part 192 provide the EPA standards for the management of wastes at active uranium and thorium processing sites (Title II sites). In addition to the EPA standards, technical criteria have been established by NRC in 10 CFR Part 40, Appendix A, pertaining to the disposition of tailings. NRC requires that tailings disposal be addressed in license applications for uranium or thorium processing facilities. The NRC criteria pertaining to groundwater protection incorporate the EPA standards and add some additional specific requirements. The NRC criteria also contain geotechnical design requirements for the disposal facility as well as financial and ownership requirements.

The primary groundwater protection standard given in Criterion 5A of 10 CFR Part 40, Appendix A, is a design standard for surface impoundments containing tailings. For new surface impoundments at active sites, a liner capable of preventing the migration of wastes into adjacent soil, groundwater, or surface water is required unless it can be shown that an alternate design will prevent the migration of any hazardous constituents into groundwater or surface water. Specific liner requirements are given by EPA regulations in 40 CFR 264.221 and by Criterion 5A in 10 CFR Part 40, Appendix A. According to Criterion 5A(1), the liner may be designed so that wastes can migrate into the liner if the site closure plan includes removal or decontamination of all wastes, contaminated liner material, and other contaminated materials. However, if the closure plan specifies closure with the liner in place, then the liner must be designed to prevent migration of wastes into the liner during the life of the disposal facility.

The secondary groundwater protection standard (Criterion 5B of 10 CFR Part 40, Appendix A) requires setting a site-specific groundwater standard similar to that required for Title I sites. The standard consists of a list of hazardous constituents, a corresponding list of concentration limits, and a point of compliance. These are specified by NRC as part of license conditions and orders.

EPA standards for Title II sites reference specific RCRA groundwater regulations (40 CFR Part 264) in addition to those applied to Title I sites. These requirements are also incorporated into the NRC criteria in 10 CFR Part 40, Appendix A. Specific requirements are given for surface impoundments, detection monitoring programs, and corrective action programs. Another difference between the Title I and Title II standards is that for Title II sites, specific concentration limits are not specified for uranium, nitrate, or molybdenum.

Additional closure requirements are found in 40 CFR 264.228 and in Criteria 5E and 6 of 10 CFR Part 40, Appendix A. Free liquids must be eliminated from the waste materials before closure. A low-permeability cover must be provided to minimize seepage. According to the RCRA regulations pertaining to closure of surface impoundments, the cover permeability must be less than the permeability of the impoundment liner. This is to prevent the buildup of residual water in the waste materials above the liner. However, for uranium mill tailings sites, an exception allows the cover to have a higher permeability than the liner if the annual evaporation at the site is greater than the total annual precipitation expected to fall on the impoundment and any drainage area contributing runoff to the impoundment [40 CFR 192.32(a)]. This exception recognizes the fact that most uranium mill tailings sites are in low-precipitation areas and moisture is not likely to build up in the waste materials if infiltration is limited by low precipitation and high evaporation rates. From the NRC's perspective, the site operator must demonstrate that excess moisture will not build up in the waste materials.

Cleanup of existing contamination is not specifically addressed in the Title II standards. However, Criterion 5D of 10 CFR Part 40, Appendix A, requires that remedial actions be implemented in cases where the site-specific groundwater standard is not exceeded. This may be applied to cases of existing groundwater contamination at a Title II site.

Leaching and Long-Term Releases of Hazardous and Radioactive Constituents From Contaminated Materials

This discussion assumes that contaminated materials in the disposal facility remain above the water table and that any residual water has already drained from the tailings. During the period following closure of a tailings disposal site, a slow displacement of the moisture remaining in the pore spaces by infiltration is expected. Infiltrating moisture is expected to mix with water in the pore spaces of the contaminated material and transport mobile constituents toward the uppermost aquifer. The dilution of water within the tailings by the added infiltration may result in undersaturation with respect to some chemical constituents and cause them to be leached from the solids.

For disposal facility design and performance assessment, both the long-term seepage rate and the concentrations of hazardous constituents expected in seepage from the contaminated materials must be determined. Assumptions made in predicting the long-term release of constituents need to be conservative. In other words, incorrect assumptions should tend to overestimate rather than underestimate releases of hazardous constituents from contaminated materials.

Long-Term Seepage Rate

The expected vertical flux of moisture, or seepage rate, through the disposal cell is normally determined as part of the required performance assessment. Both the natural setting and the engineering design of the disposal facility affect the seepage rate. Two important aspects of the natural setting are the amounts of precipitation and evapotranspiration. These climatic factors may determine whether components of the disposal facility operate under saturated or unsaturated conditions. Topography can also affect seepage rate by causing surface runoff to be "ponded" on top of the disposal facility. Low-temperature conditions can result in frost disturbance of the cover leading to increased permeability and seepage rates. The most important engineered factor affecting seepage rate is usually the cover. Many cover designs employ an infiltration barrier specifically designed to limit seepage. However, conditions under which the contaminated materials are placed (i.e., moisture content and compaction) can also have a significant effect.

The following acceptance criteria are applicable to seepage rate determination.

Criterion 1 - Assumed conditions of cover operation should be realistic and conservative.

Either saturated, unsaturated, or intermittently saturated flow conditions must be assumed for each of the disposal facility components in the performance assessment. This assumption is particularly important for the infiltration barrier or other components designed to limit seepage. If unsaturated or intermittently saturated conditions are assumed for the infiltration barrier, a numerical model designed to simulate unsaturated flow may be used to predict the seepage rate. However, uncertainties in boundary conditions and in the validity of assumptions used in the model often make it difficult to do this in practice. Transient conditions are likely, because increases in moisture content and seepage rate would be expected following rainfall or snowmelt events. Because of these difficulties, seepage rate is often calculated assuming saturated flow conditions through the infiltration barrier.

If saturated flow conditions are assumed for the infiltration barrier, a constant hydraulic gradient of unity is normally used to calculate the infiltration rate. The moisture flux through the tailings is then equal to the saturated hydraulic conductivity of the infiltration barrier. Such an assumption of saturated flow in the infiltration barrier is usually considered conservative because it assumes that enough moisture is available at the surface of the barrier to keep it constantly saturated.

If seepage rate is determined assuming unsaturated flow conditions, it must be demonstrated that the cover will remain unsaturated over the design life of the facility and the transient moisture content must be predicted. Simply calculating the seepage rate based on the unsaturated hydraulic conductivity at the initial water content of the material is not sufficient. It is likely that the moisture content will change over time. An assumption of unsaturated conditions must be supported by accurate hydraulic property and climatic data. The configuration of the disposal facility and natural topography of the site should also be considered to ensure that ponding of water will not cause saturated conditions. To enhance runoff of precipitation from the cover, a filter layer of coarse material is often provided above the low-permeability infiltration barrier. However, slopes must be sufficient to allow runoff;

otherwise, the filter layer might keep ponded water on top of the disposal facility from evaporating and result in saturated conditions.

If intermittently saturated conditions are assumed, a verified two-phase flow model capable of simulating transient flow conditions is needed to simulate seepage rate over time. Boundary conditions must be accurately defined. The availability of water at the top of the infiltration barrier must be supported by climatic data (see Criterion 4). It must be shown that simplifications made by the model and inaccuracy in the input data tend to overestimate rather than underestimate releases of hazardous constituents.

Criterion 2 - Samples for determining hydraulic and physical properties of the infiltration barrier must be representative.

At the design stage, the physical and hydraulic properties of the material to be used for the infiltration barrier must normally be determined from laboratory testing of samples collected from the proposed borrow area. The entire volume of material to be used in constructing the infiltration barrier must be included in the selection of sampling locations. Sample locations should be selected by a random or systematic method (Bruner 1986; EPA 1990). For systematic sampling, the material is divided into a grid and samples collected by a predefined pattern. For random sampling, the volume may be divided into a finer grid and samples collected from grid points chosen by a random number generator. Either method should result in an unbiased selection of samples. However, systematic sampling can be affected by patterns in the distribution of materials within the borrow area. Samples taken from haphazardly chosen locations may reflect a conscious or subconscious favoritism that would make the samples unrepresentative.

The number of test samples must be adequate to determine average hydraulic properties of the infiltration barrier material within an acceptable uncertainty level. The number of samples required depends on several factors, including the volume of material required, spacial variability, and the tolerance of the performance assessment to variations in infiltration barrier properties. The distribution type and the mean, standard deviation, and standard deviation of the mean should be determined from statistical analysis of the test results (EPA 1990). The confidence level that the mean is within the range assumed by the performance assessment can then be determined.

Procedures for sample preparation should be described. The procedures should assure that the test results will be representative of actual infiltration barrier properties. Any planned soil amendments, such as bentonite, should be added to the samples using a method similar to that proposed for construction. Moisture content and compaction should simulate that of the planned infiltration barrier. At equal compaction (dry bulk density), the unsaturated hydraulic conductivity will be greater for higher moisture content. Therefore, testing wet of optimum moisture content is considered conservative, where the optimum moisture content is that which results in the greatest possible compaction. Laboratory compaction procedures are considered adequate if the same compaction and moisture content can be achieved in the field.

Criterion 3 - The hydraulic conductivity of the infiltration barrier must be based on accepted test methods.

Hydraulic conductivity is the parameter that corresponds most closely with seepage rate. Whether the saturated or unsaturated hydraulic conductivity should be determined depends on the assumptions of the performance assessment for the disposal facility.

Laboratory test methods for determining hydraulic conductivity of the infiltration barrier materials should be accepted standard methods. If the design assumes that the cover will operate under saturated conditions, the saturated hydraulic conductivity should be determined using either the constant-head or falling-head methods employing a flexible-wall permeameter (ASTM D5084). Methods employing rigid-wall permeameters are subject to errors caused by flow along the vessel wall, especially if the sample shrinks. Stresses applied to the samples should simulate expected field conditions. Excessive hydraulic gradients may affect test results by compacting the sample or by washing out particles. These effects could increase or decrease sample permeability. However, it is often not possible to test low-permeability materials in a reasonable amount of time under expected field gradients. For this reason, the test method in ASTM D5084 gives a guideline of 30 for the maximum test gradient for materials with hydraulic conductivities less than 1E-7 cm/s. Lower maximum gradients are specified for more permeable materials.

Testing can be performed at different gradients on the same sample to determine whether an excessive gradient has an effect.

Determining saturated hydraulic conductivity by the permeameter method is relatively simple and reliable in comparison to determining unsaturated hydraulic conductivity. Assuming that saturated conditions exist in the cover is generally considered a conservative assumption, because the hydraulic conductivity under unsaturated conditions is always lower than the saturated hydraulic conductivity. Therefore, the saturated hydraulic conductivity is an upper limit for unsaturated hydraulic conductivity of the same material.

If unsaturated conditions are assumed for the performance assessment of the infiltration barrier, then the relationship of hydraulic conductivity to moisture content must be determined. Both the unsaturated hydraulic conductivity and the moisture content of an unsaturated porous media are functions of the pressure (suction) head. Furthermore, these relationships, or characteristic curves, are hysteretic, i.e., they have different shapes for drying and for wetting. Because unsaturated hydraulic conductivity and moisture content are both functions of pressure head, the unsaturated hydraulic conductivity can be expressed as a function of moisture content. This relationship is not very hysteretic. A single value of hydraulic conductivity corresponds to a particular moisture content regardless of whether the sample is undergoing drying or wetting.

The relationship of unsaturated hydraulic conductivity to moisture content is normally determined by first measuring the moisture content of the sample at a number of pressure heads. ASTM D3152 or a similar procedure may be used. The moisture characteristic curve is then fitted to the experimental data. The relationship of moisture content to hydraulic conductivity is determined from the moisture characteristic curve using a technique such as that described by van Genuchten and Nielsen (1985). Curves of moisture content versus hydraulic conductivity can also be determined from direct measurement in the laboratory of unsaturated conductivity at various moisture contents.

Criterion 4 - Site climatic conditions must be characterized well enough to support design and performance assessment calculations of the moisture flux.

Climatic conditions, including precipitation and evapotranspiration rates, and the distribution of precipitation over time affect the amount of water infiltrating the disposal facility. If an unsaturated flow model is used to determine moisture flux, it may be necessary to define a boundary condition at the surface of the cover based on precipitation and evapotranspiration. The distribution of rainfall and snowmelt over time may be particularly important. This is because most tailings disposal sites are located in arid regions where the annual evapotranspiration is much greater than the annual precipitation. The only time infiltration is likely is during or immediately following a relatively sustained event of rainfall or snowmelt.

Representative climatic data must be obtained from a nearby recording station with weather conditions similar to those of the site. The weather station should be located within the same type of terrain and at about the same elevation as the site. If such data are not available and climatic parameters must be assumed from regional information, then it should be demonstrated that the assumed values are conservative.

Criterion 5 - The disposal facility must be designed so that excess moisture will not build up in the contaminated materials.

If the infiltration rate through the cover is greater than the rate at which moisture can drain from the disposal facility, excess moisture can build up in the contaminated materials. A saturated zone might be created within the contaminated materials with water containing high concentrations of hazardous constituents. Surface seepage of contaminated water could also result.

To guard against this situation, the surface impoundment regulations in 40 CFR 264.228(a)(2)(iii) specify that cover permeability must be less than the permeability of any liner or natural subsoil underlying the impoundment. This requirement is waived for Title II uranium mill tailings facilities if the annual evaporation at the site is greater than the total annual precipitation falling on the impoundment and any drainage area that contributes surface runoff to the impoundment [40 CFR 192.32(a)]. However, the actual potential for buildup of moisture in the contaminated materials depends on the difference between infiltration through the cover and seepage through the underlying layer. Infiltration may take place even if the annual evaporation is greater than the annual precipitation. The infiltration rate will depend on the temporal distribution of rainfall and snowmelt and on cover conditions. Even in dry climate areas, the infiltration could be greater than the seepage from the bottom of the contaminated materials. Therefore, accurately predicted infiltration and seepage rates should be compared to show that moisture will not build up in the contaminated materials.

Criterion 6 - Calculations of infiltration rate must be conservative.

Potential errors and sources of inaccuracy in the determination of infiltration rate should be identified. It should be demonstrated that the infiltration rate used in the performance assessment is conservative in that these errors will tend to overestimate rather than underestimate releases of hazardous constituents. Accuracy and precision of laboratory test methods, statistical distribution of sample results, and assumptions made in modeling should be considered.

The infiltration rate used in the performance assessment is usually based on laboratory permeability measurements. Some studies (Herzog and Morse 1986; EPA 1988; Rogowski 1990) have indicated that laboratory measurements underestimate the field permeability of compacted soils. Laboratory test samples lack larger-scale heterogeneity that can cause increased field permeability. This possible inaccuracy should be considered in the facility design.

Criterion 7 - As-built hydraulic properties critical t the performance of the disposal facility should be verified.

To verify that hydraulic properties of the dispo al facility are close to those used in design calculations, a commitment should be made to determine the as-built properties, particularly hydraulic conductivity, of the infiltration barrier and other cell components that are important fc meeting the groundwater protection standards. Testing may be conducted by boring into the disposal facility to perform in situ tests or to take samples for laboratory analysis. However, the testing and sampling procedures must ensure that integrity of the cover is not compromised. Test plots constructed using the same methods and materials as the disposal cell may be used for sampling and testing to avoid disturbing the disposal facility.

Hydraulic conductivity is usually the most important property in controlling seepage rate. As-built hydraulic conductivity of the infiltration barrier may be determined either from field tests or from laboratory permeability testing of samples taken from the barrier. However, field methods are considered more reliable for representing the as-built hydraulic conductivity. Laboratory methods generally test much smaller samples, and the samples are often disturbed in collection and handling. As mentioned above, some studies indicate that laboratory tests underestimate field-scale permeability.

Field methods commonly used for determining saturated hydraulic conductivity in the vadose zone are described in ASTM D 5126. The double-ring infiltrometer method (ASTM D 3385) and the double tube method described by Bouwer (1964) are considered superior to the single-ring infiltrometer method because they are not affected as much by lateral flow (Bouwer 1966). In general, larger ring diameters reduce the effects of lateral flow for both single- and double-ring infiltrometers.

If the performance assessment relies on unsaturated flow at particular assumed moisture contents to limit seepage rate, in situ moisture monitoring may be required to assure that the cover is performing as designed. Although the performance standards in 40 CFR Part 192 and Appendix A of 10 CFR Part 40 are design standards, performance monitoring may be the only way to eliminate uncertainty inherent in the existing methodology for predicting unsaturated flow rates. DOE (1989) maintains that moisture monitoring conducted at the Shiprock, New Mexico, site can be applied at other sites with similar climates. However, these results have not been accepted by NRC as a means for demonstrating the performance of a similar cover design at another site because of differences in materials and site conditions.

Criterion 8 - Materials used to limit seepage through the disposal facility must be stable over the design life of the facility.

To satisfy the closure performance standard, DOE or the Title II site operator must show that the design will be effective for the designed disposal period of 200 to 1000 years [40 CFR 192.02(a); 10 CFR, Part 40, Appendix A, Criterion 6] and minimize maintenance [40 CFR 264.111(a); 10 CFR, Part 40, Appendix A, Criterion 12]. Long-term releases of hazardous and radioactive components might increase because of a breakdown of the infiltration barrier. The long-term stability and maintenance requirements are normally met if natural materials are used. Potential mechanisms for increased permeability, such as cracking or biointrusion, should be considered in the design of the cover.

Expected Concentrations of Constituents in Seepage

For both Title I and Title II sites, potential hazardous constituents must be identified. The concentrations of these constituents in seepage from the disposal facility must usually be predicted to support the performance assessment. These "source" concentrations may be determined through sampling of residual pore water contained in the disposed material, or through batch or column leach tests. DOE has previously noted the possibility of back-calculating the concentration in seepage from sampling of contaminated groundwater in the aquifer under the contaminated materials (DOE 1989). However, this technique would require accounting for dilution by underflow through the aquifer and geochemical attenuation. DOE would also have to show that the mass of constituents in seepage reaching the uppermost aquifer is at steady-state and not expected to increase with time.

The following acceptance criteria apply to the identification of potential hazardous constituents and determination of expected concentrations in long-term seepage.

Criterion 9 - All hazardous constituents that are reasonably expected to be in or derived from the residual radioactive material must be identified.

Proposed EPA regulations (40 CFR Part 192) implement the RCRA definition of hazardous constituents for both Title I and Title II sites. This definition is given in 40 CFR 264.93a. A nearly identical definition is given in NRC regulations in 10 CFR Part 40, Appendix A, Criterion 5B(2). Based on these definitions, a constituent becomes hazardous when all of the following conditions are met.

- It has been detected in the uppermost aquifer.
- It is reasonably expected to be present in or derived from the waste (byproduct) materials.
- It is $^{226/228}$Ra, $^{234/238}$U, nitrate, molybdenum, or gross alpha activity, or is listed in Appendix VIII of 40 CFR Part 261 (or Criterion 13 of 10 CFR Part 40, Appendix A).

Although a constituent does not technically become a hazardous constituent until it is detected in the uppermost aquifer, potential hazardous constituents must be identified so that detection monitoring can be implemented.

The nature of the waste material must be considered in determining potential hazardous constituents. Tailings and other residual contaminated materials are potential sources of metals, inorganic nonmetals, and radionuclides (Shepherd and Cherry 1980). Organics may also be present from uranium extraction processes.

The specific hazardous constituents present in residual radioactive materials at a site depends primarily on the compounds present in the ore and the constituents added during milling. Uranium ore may be milled using either alkaline or acidic leach solutions. The process used will affect the pH of the tailings and the solubility of many hazardous constituents (Shepherd and Cherry 1980). Nearly all uranium mills in the United States use an acid leach process. Tailings solutions from these mills generally have a pH of less than 2 (Shepherd and Cherry 1980). Radionuclides commonly found in relatively high concentrations in tailings from acid leach mills are ^{226}Ra, ^{210}Pb, ^{210}Po, ^{230}Th, and uranium (IAEA 1987). Although ^{210}Pb, ^{210}Po, and ^{230}Th are not specifically listed in the regulations, they contribute to alpha activity. Regulated metals including barium, beryllium, cadmium, chromium, nickel, antimony, lead, mercury, silver, molybdenum, and vanadium (vanadium pentoxide is the regulated compound) may be found in elevated concentrations, as may the regulated nonmetals nitrate, cyanide, selenium, and arsenic. Extremely high concentrations of total dissolved solids are common in tailings water. For acid leach mills, this is mainly sulfate from the addition of sulfuric acid.

Organic tertiary amines are commonly used to extract uranium from the pregnant solution in uranium milling (Galkin et al. 1966). If this process is used, a dilutant such as benzene or kerosene is mixed with the amine. The amine and dilutant mixture is nor[illegible]used and does not go into the disposal facility. However, accidental releases and dissolution might lead to the presence of organic constituents in the tailings. Coincidental operations at the site, such as maintenance activities, might also result in the presence of other listed constituents. These constituents should be considered in the detection monitoring program if there is evidence that they exist in the disposal facility and have resulted from the uranium processing operation.

Criterion 10 - Concentrations of hazardous constituents expected in seepage must be conservatively determined from pore water samples or from leach tests.

Pore Water Sampling

Assuming that the concentration of constituents in long-term seepage will equal that of residual pore water contained in the contaminated materials is generally considered a conservative assumption. Dissolved constituents are expected to be at saturation in the pore water if a solute source is present. Expected changes in geochemical conditions (i.e., dilution and neutralization) will generally reduce the solubility and mobility of most inorganic constituents. However, if pore water concentrations have been diluted by higher than normal infiltration, this technique may not give a conservative estimate of hazardous constituent concentrations.

Samples of residual pore water are usually taken from suction lysimeters. The number of samples should be sufficient to characterize the chemistry of the water. DOE (1989) specifies collection from a minimum of three sampling locations in the tailings and one location in each of the other potential sources of hazardous constituents. However, more sampling locations may be needed, especially if there is a lack of homogeneity in the materials sampled. Tailings may become segregated by particle size as they settle in a tailings pond. Distance from the outfall can also affect the particle size distribution of tailings. Higher concentrations of hazardous constituents are expected in the finer-grained materials (slimes). The spatial distribution, depth, and type of material sampled should be checked to determine that samples are representative and that an unbiased method was used to select sampling locations. Because of drainage and evaporation, it may not be possible to collect residual moisture samples from the upper portions of the tailings. This could bias the results of pore-water sampling.

Long-term changes in geochemical conditions within the contaminated materials might affect the release rate of hazardous and radioactive constituents. However, most expected chemical interactions will tend to demobilize, rather than mobilize, hazardous constituents. Neutralization of acidic residual tailings fluid is probably the most significant mechanism in demobilizing hazardous and radioactive constituents. The tailings fluid discharged by acid leach mills normally has a pH between 0.5 and 2.0 (Shepherd and Cherry 1980). In this low pH range, many constituents are dissolved that would be precipitated at near neutral pH values. The solubilities of arsenic, selenium, cadmium, cobalt, chromium, copper, molybdenum, lead, vanadium, and zinc have been shown to be reduced by neutralization (Opitz et al. 1985). Radionuclides including ^{226}Ra, ^{210}Pb, ^{230}Th, and uranium are also largely removed from solution at near-neutral pH. Therefore, sampling of pore water is expected to give a conservatively high value for expected constituent concentrations as long as the collected samples are representative.

Leach Tests

Laboratory leach tests of samples of contaminated materials may also be used to determine source concentrations of hazardous and radioactive constituents. Either batch or column leach tests may be used. Batch tests are generally more conservative because the leach solution is in contact with the waste sample for a longer period of time. Column tests may be affected by reaction kinetics if the fluid flows through the sample too quickly. Geochemical conditions during leach tests (i.e., pH and Eh) should simulate the expected conditions within the disposal facility. DOE (1989) states that "source concentrations calculated from batch and column tests should be adjusted to account for dilution of the original sample moisture by additional pore volumes." This procedure would be conservative in determining source concentrations because dilution by added pore volumes may result in the leach solution becoming undersaturated and additional constituent mass being dissolved. A concentration somewhat higher than the actual source concentration would then be calculated based on the original moisture content. Source concentrations might be underestimated if a correction is not made for dilution by added water.

The total leachable mass of a particular constituent contained in the disposal facility can also be calculated from leach tests. Knowing the total leachable mass can be useful in determining whether the total reaction or exchange potential along the groundwater flow path is sufficient to remove the constituent from solution.

Criterion 11 - Samples for determining hazardous constituent concentrations expected in seepage must be representative of the waste materials.

Samples, whether composed of solid waste materials or pore water, must be representative of the contaminated materials. The number of samples required depends on the volume of waste material and the spacial variability of the contaminant concentrations. Sampling locations should be selected by an unbiased method. The entire volume of waste material should be included in the selection process. Sample locations can be selected by a random or systematic method (Bruner 1986; EPA 1990). For systematic sampling, the material should be divided into a grid and samples collected by a predefined pattern. For random sampling, the volume should be divided into a finer grid. Samples should be collected from grid points chosen by a random number generator. Either method should result in an unbiased selection of samples. Samples taken from haphazardly chosen locations may reflect a conscious or subconscious favoritism that would make the samples unrepresentative.

The number of test samples must be adequate to determine average concentrations of potential hazardous constituents within an acceptable uncertainty level. The assumed distribution type, mean, standard deviation, and standard deviation of the mean should be determined from statistical analysis of the test results (EPA 1990). The confidence level that the mean is within the range assumed by the performance assessment can then be determined.

Hazardous and radioactive constituents released from the contaminated materials will be transported by seepage through the unsaturated zone and, subsequently, by groundwater flow in the saturated zone. During transport, physical, geochemical, and biological processes can contribute to the reduction of constituent concentrations. Physical processes that may reduce constituent concentrations in groundwater include dilution and radioactive decay. Geochemical processes include precipitation, co-precipitation, and adsorption. Biological activity of microorganisms in the soil can also remove constituents from solution. One or more of these processes may be used in the performance assessment to show that the groundwater standard will be met for the design life of the facility.

One of two possible strategies are generally used to demonstrate that a particular disposal design, together with natural site conditions, will result in the concentrations of hazardous constituents at the point of compliance remaining lower than the established concentration limits. The strategy used will determine what attenuation processes are pertinent to the performance assessment.

The first possible strategy consists of showing that under steady-state flow and transport conditions, hazardous constituents will remain indefinitely at concentrations lower than the established limits at the point of compliance. This might be called the dilution strategy, because dilution of transported contaminants by background flow through the uppermost aquifer is usually important in reducing concentrations to acceptable levels. Travel time is generally not an important factor if this strategy is employed. Average long-term seepage rate through contaminated materials and the release rate of hazardous constituents from the tailings are important, as are the steady-state background flow rate in the uppermost aquifer, the background concentrations of regulated constituents in the uppermost aquifer, and geochemical processes that reduce constituent concentrations. Irreversible sorption and precipitation of contaminants may be important. However, a process such as reversible sorption, which only slows down transport, would not be helpful in showing that the concentration at the point of compliance will remain permanently below the allowable limit.

The second possible strategy for demonstrating compliance with groundwater protection standards is to show that hazardous constituents will move so slowly that they will not reach the point of compliance in concentrations greater than the established limits before the end of the required 200- to 1000-year containment period. This may be called the "long travel-time strategy." Important factors include seepage rate through the cover, travel time through the unsaturated zone, average groundwater velocity through the saturated zone, and geochemical attenuation processes that slow contaminant transport. Dilution processes are usually not as important to this strategy because it relies on average travel time.

The following acceptance criterion relates to establishing a minimum control period for performance of the disposal facility.

Criterion 12 - The disposal facility must be designed to provide control that is effective for 1000 years, to the extent reasonably achievable, and, in any case, for at least 200 years.

The proposed EPA Standard [40 CFR 192.02(a)] for Title I states that "Control of residual radioactive materials and their listed constituents shall be designed" to meet this longevity criterion. For Title II sites, Appendix A of 10 CFR Part 40 specifies that the design must provide "reasonable assurance of control of radiological hazards" for this time period. If an effective period of less than 1000 years is chosen, DOE or the Title II site operator must demonstrate that a design that would be effective for a longer period is not "reasonably achievable." Possible design changes should be evaluated to determine if any reasonable change would result in a longer effective control period. Possible design changes include relocation, cover material and thickness, addition of layers of buffer material, addition of a liner, and configuration of the disposal.

If the "dilution strategy" is used, the control period may not be an important consideration because the concentrations of hazardous and radioactive constituents would be shown to remain below allowable limits indefinitely.

Physical Attenuation Processes

Dilution and radioactive decay are physical processes that can reduce the concentrations of some constituents before they reach the point of compliance. However, the half-lives of most radioactive constituents of concern in uranium processing waste are much longer than the 1000-year period specified for control of hazards. Therefore, radioactive decay is not expected to significantly reduce the concentrations of these constituents. The possible exceptions are ^{226}Ra with a 1602-year half-life, ^{210}Pb with a 21-year half-life, and ^{210}Po with a 138-day half-life.

Seepage water from a disposal facility may be diluted by mixing with water flowing through the uppermost aquifer. This is often an important factor in showing that concentrations of hazardous constituents will be below concentration limits at the point of compliance. Dilution of a dissolved constituent in groundwater takes place through molecular diffusion and mechanical dispersion. These processes will cause a plume to spread out and affect a wider area. The maximum concentration of the plume may be reduced. Mechanical dispersion and molecular diffusion also can cause a hazardous constituent, in reduced concentration, to reach the point of compliance in a shorter travel time than that predicted by the "average" groundwater velocity.

Mechanical Dispersion

The mechanical dispersion component of dilution results from the velocity distribution of water traveling through a pore space, and from water following different microscopic flow paths. Mechanical dispersion may also be caused by larger-scale heterogeneity in the formation. Therefore, dispersion has been found to be scale dependent (Kahn and Jury 1990), increasing with the distance from the source.

The following acceptance criterion relates to quantifying the effects of mechanical dispersion:

Criterion 13 - If mechanical dispersion is important in the performance assessment, dispersivity values must be representative of the porous media.

Mechanical dispersion may be used in the performance assessment to show that a hazardous constituent will be diluted in the uppermost aquifer, resulting in the maximum concentration at the point of compliance remaining below the established concentration limit. Dispersivity is the aquifer parameter that quantifies the tendency for mechanical dispersion in the saturated zone. Dispersivity is a function of average groundwater velocity, average particle size, particle-size uniformity, aquifer heterogeneity, and system scale. Dispersivity values generally increase with the scale of the flow system.

Laboratory column experiments with a nonreactive tracer can be conducted to obtain longitudinal dispersivity values. However, there are two problems with this methodology: 1) disturbance of the geologic material during sampling and laboratory handling may change the dispersivity, and 2) laboratory-scale experiments will not reflect larger-scale heterogeneities. Because of these limitations, laboratory-determined values are not very useful for predicting mechanical dispersion at the scale of interest. Dispersivity values should increase at a larger scale. Therefore, laboratory dispersivity values from carefully handled samples might be used as a lower limit for field-scale dispersivity. Assuming a lower value of dispersivity is conservative because greater mechanical dispersion normally increases dilution and reduces constituent concentrations at the point of compliance.

Tracer tests have also been employed to determine dispersivity values on a larger scale. The biggest drawbacks to tracer tests are: 1) the long time period required to conduct the test, especially under natural gradient conditions, and 2) possible disturbance of the flow system if strenuous injection and pumping are applied to speed tracer movement. Dispersivity values, both longitudinal and transverse, obtained from properly conducted tracer tests, are considered more accurate than laboratory tests. Again, tracer tests on a smaller scale than the performance assessment calculations should give lower limit values for dispersivity.

Mechanical dispersion in the unsaturated zone is not as well understood as dispersion in the saturated zone and would be difficult to apply quantitatively to the performance assessment.

Dispersivity values used in the performance assessment must be based on sampling and testing procedures that accurately represent the aquifer. Uncertainty in the measurements must be considered so that dispersion calculations are conservative. That is, calculated concentrations at the point of compliance should be maximized by the uncertainty.

Molecular Diffusion

Molecular diffusion is the movement of dissolved particles from regions of higher concentration to regions of lower concentration as a result of molecular motion. In relatively permeable media, the effect of molecular diffusion is usually much less than the effect of mechanical dispersion. However, at low groundwater flow velocities, diffusion may become the dominant transport mechanism. In the absence of significant groundwater flow, a dissolved constituent may move by molecular diffusion alone. The following criterion requires consideration of diffusion driven transport.

Criterion 14 - Diffusion of constituents should be considered as a possible transport mechanism.

If the long travel-time strategy is used, the possibility of molecular diffusion causing dissolved constituents to travel faster than the average groundwater velocity to the point of compliance should be considered. Diffusion can be a significant transport process if the average flow rate of the groundwater is less than a few tens of meters per year.

Diffusion of a solute in water is described mathematically by Fick's first law, expressed in one dimension as:

$$F = -D\ (dC/dx)$$

where

F = Mass flux $[M/L^2T]$
D = Diffusion coefficient $[L^2/T]$
dC/dx = Concentration gradient $[M/L^4]$

The diffusion coefficient, D, is temperature dependent because it results from molecular motion. Diffusion coefficients for many solutes in water are available in the literature. In saturated porous media, however, the solid matrix reduces diffusion. Therefore, the diffusion coefficient in Fick's Law should be replaced by the apparent diffusion coefficient, d', which is normally about 1% to 50% of the diffusion coefficient in water (Freeze and Cherry 1979). Adsorption of the chemical species will also reduce the diffusion coefficient.

Freeze and Cherry (1979) calculate diffusion-driven transport for a hypothetical example in which one strata contains a species at constant concentration C_0 and an adjacent strata initially has concentration of zero. The concentration in the adjacent strata at time t and at distance x from the source strata is given by (Crank 1956) as

$$Ci(x,t) = C_0 \text{ erfc } [x/2 \text{ sqr}(D't)]$$

where erfc is the complementary error function. The apparent diffusion coefficient is assumed to be 5E-10 m^2/s. This is representative of a nonsorbed species in a sandy formation. The results of this example show that after 500 years the concentration at a 10-m distance from the source strata would be about 10% of the source concentration.

Geochemical Attenuation Processes

Geochemical attenuation may result from precipitation, co-precipitation, and adsorption (ion-exchange) of hazardous and radioactive constituents as water travels through the unsaturated and saturated zones. These processes are affected by overall geochemical conditions such as pH and reduction-oxidation potential (Eh). Because geochemical conditions may differ between the contaminated materials, the unsaturated zone, and the uppermost aquifer, the effects of geochemical attenuation may change along the flow path.

Criterion 15 - Geochemical processes assumed to remove constituents or slow transport must be supported by reliable geochemical characterization data.

Constituents from the contaminated materials will be transported toward the uppermost aquifer by seepage through the disposal facility. If precipitation, co-precipitation, or adsorption are assumed to remove or slow the transport of constituents, DOE or the Title II facility operator must show that geochemical conditions along the expected flow path are such that these processes will take place. For example, if precipitation of uranium salts is predicted as a result of neutralization as seepage moves through the unsaturated zone, it must be demonstrated that minerals within the unsaturated zone will result in changes in the chemistry (i.e., pH) of the fluid resulting in precipitation of uranium.

For Title II sites, Criterion 5G in 10 CFR Part 40, Appendix A, mandates that the applicant shall supply information concerning "the characteristics of the underlying soil and geologic formations particularly as they will control transport of contaminants and solutions". The same paragraph states that "Testing must be conducted to allow estimating chemisorption attenuation properties of underlying soil and rock."

Precipitation

Precipitation refers to the separation of a dissolved constituent from solution by formation of a solid reaction product. Precipitation of hazardous and radioactive constituents caused by neutralization of acidic tailings solution is probably the most important attenuation mechanism at uranium tailings sites in the United States. The tailings fluid discharged by acid leach mills normally has a pH between 0.5 and 2 (Shepherd and Cherry 1980). Neutralization to near neutral pH will cause precipitation of most of the ^{226}Ra, ^{210}Pb, ^{230}Th, uranium, arsenic, selenium, cadmium, cobalt, chromium, copper, molybdenum, lead, vanadium, and zinc contained in typical tailings solution (Opitz et al. 1985). A field study of radionuclide attenuation in the vicinity of a uranium mill tailings site (Haji-Djafari et al. 1981) found that pH was the most important factor in controlling the transport of hazardous constituents from a tailings pond.

Neutralization of seepage from a disposal facility is caused mainly by contact with minerals containing CO_3^{-2} and OH^-. These species react with soluble cations to form compounds that have very low solubility at near neutral pH. The concentrations of constituents at any point along the flow path will be determined by the solubility of compounds under the existing chemical conditions at that point. Groundwater transport models that incorporate geochemical equilibrium may be used to predict transport. However, it must be demonstrated that assumptions of the model are conservative and are based on an accurate geochemical characterization of the disposal site.

Co-Precipitation

Co-precipitation occurs when a constituent is incorporated into the mineral structure of another precipitating compound. An example of a common reaction involving solution from uranium mill tailings is the precipitation of $CaSO_4$ (Shepherd and Cherry 1980). The tailings fluid typically contains a high concentration of SO_4^{-2} and H^+ ions. If $CaCO_3$ minerals are encountered, the acidic solution is neutralized and $CaSO_4$ precipitates. Radium will replace some of the Ca^{+2} ions in the precipitated solid. Because of the large mass of sulfate present, a significant amount of radium can be removed from solution by this process. Neutralization caused precipitation of iron and manganese oxides can also cause the co-precipitation of significant amounts of contaminants. However, the effects of co-precipitation are difficult to determine quantitatively and it is difficult to predict the degree to which this mechanism will remove constituents. Therefore, this mechanism would be difficult to quantify in a performance assessment.

Adsorption

Adsorption refers to the accumulation of ions, particularly cations, on the surface of charged colloidal-sized particles. Most clay minerals are of colloidal size. Some hazardous ionic constituents have a stronger affinity for the charged colloidal particles and will replace adsorbed ions through an ion exchange process. Therefore, adsorption can result in attenuation of hazardous constituents as they move through the unsaturated or saturated zones. Ion exchange may be reversible or irreversible. If the exchange is reversible, then the adsorbed ion will eventually be released and replaced by another ion. Therefore, the effect of reversible sorption is to retard the movement of the contaminant relative to the average velocity of groundwater.

The distribution coefficient, K_d, or the distribution function, K_f, is used to quantify the adsorption of a particular constituent by a solid porous material. Laboratory tests are normally used to derive these parameters for the specific porous material. A solution containing a known concentration of the constituent is mixed with a known mass of the solid material and allowed to equilibrate. The concentration remaining in solution is measured and the adsorbed concentration determined. This is repeated for several different initial concentrations. A plot, called an adsorption isotherm, is then made showing solution concentration versus adsorbed concentration. The slope of this line, if constant, is the K_d. If the plot is non-linear, then it defines the K_f. If adsorption of a particular constituent can be described by a linear isotherm, the K_d can be used to determine the rate of movement of the constituent from the following equation:

$$v_c = v/(1+K_d(\rho/n))$$

where

v_c = average velocity of constituent [L/T]
v = average groundwater velocity [L/T]
K_d = distribution coefficient [L^3/M]
ρ = dry density of solids [M/L^3]
n = porosity

This equation is only applicable for constituents at low concentration and for water of similar chemical composition to that used in determining the K_d. If the concentration is too high, all possible exchange sites may be occupied, resulting in excess constituent molecules in solution that are not subject to adsorption. These assumptions are often not met in studies of constituent transport from tailings impoundments because of the initial high dissolved solids content and the changing composition caused by neutralization of acidic tailings. Acidic conditions generally reduce adsorption because H^+ ions displace the constituent molecules from exchange sites.

Criterion 16 - If neutralization or ion exchange processes are assumed to slow or remove constituents, it must be demonstrated that sufficient neutralization or exchange capacity exits.

DOE or the Title II operator must demonstrate that the mass of materials that will come in contact with contaminated seepage from the disposal facility has sufficient capacity to meet the design assumptions for attenuation of hazardous and radioactive constituents.

Using the long travel-time strategy, geochemical attenuation processes may be reversible and still result in slowing of contaminant transport. However, the capacity must be sufficient to slow transport to the degree assumed by the analysis.

The possibility that preferential flow paths through the unsaturated zone might decrease the mass of reactive mineral material contacted by contaminants should also be considered. Theoretical and laboratory studies (Glass et al. 1989) have shown that wetting front instability or fingering may develop as water flows through the unsaturated zone. This phenomenon is likely to occur for a certain vertical distance below the contact of a fine-grained material overlying a more coarse-grained material. The finger widths can be predicted from linear stability theory (Glass et al. 1989; Glass et al. 1990).

Groundwater Monitoring Programs

A groundwater monitoring program must be implemented at disposal sites to 1) establish baseline conditions, 2) allow the detection of released hazardous constituents in the uppermost aquifer, 3) ensure that groundwater protection standards are met, and 4) evaluate the effectiveness of any required corrective actions. For Title I sites, EPA regulations require monitoring to "establish background water quality" [40 CFR 192.20(a)(2)] and to "demonstrate that initial performance of the disposal is in accordance with the design requirements..." [40 CFR 192.02(b)]. For Title II sites, Criterion 7 of 10 CFR Part 40, Appendix A, mandates programs for baseline monitoring, detection monitoring, compliance monitoring, and corrective action monitoring.

Baseline Monitoring

The following acceptance criteria are related to establishing baseline groundwater conditions at Title I or Title II disposal sites.

Criterion 17 - Adequate hydrogeologic information must be provided concerning the soil and geologic formations underlying the proposed disposal site.

This requirement is specified for Title II sites in Criterion 5G of 10 CFR Part 40, Appendix A. Detailed information on the thickness, orientation, uniformity, extent, hydraulic conductivity, and hydraulic gradient is required. This information must be obtained from drilling of boreholes as well as from surface methods. The hydraulic conductivity must be determined from a "sufficient amount of field testing (e.g., pump tests)" and not exclusively from laboratory testing of samples. The requirements for hydrogeologic characterization at Title I sites are not spelled out as specifically. However, adequate information is required to support the effectiveness of proposed groundwater monitoring and the performance assessment calculations.

Hydraulic conductivity, and sometimes storativity, can be determined from various types of borehole hydraulic tests. Test methods include constant flow rate (Cooper and Jacob 1946), constant head (Jacob and Lohman 1952), slug (Cooper et al. 1967; Bouwer and Rice 1976), and pulse tests (Bredehoeft and Papadopulos 1980). Many analysis techniques are described in the literature for these basic test types. A method for conducting constant-head injection tests is described in ASTM D 4630. Techniques for pulse tests are described in ASTM D 4631.

Slug and pulse tests have a smaller radius of influence and are therefore not as desirable as constant rate and constant head tests for determining hydraulic properties. However, slug and pulse tests do not result in the removal of large volumes of water from the aquifer. This can be an advantage if the water is contaminated.

Constant rate tests are generally best for identifying aquifer characteristics. Multiple well tests, using a pumped well and one or more observation wells, test the largest volume and minimize borehole effects. Multiple well tests are generally required for accurate determination of storativity. In low-permeability formations it may not be possible to remove water at a sustainable rate needed for a constant rate test. Constant rate injection tests are then desirable.

Analysis of borehole hydraulic tests must be correctly performed and analyzed with consideration of the underlying assumptions. This is especially true for the straight-line analysis method (Cooper and Jacob 1946; Miller et al. 1950; Horner 1951) for constant rate tests, which is often misapplied. The straight-line analysis method is valid for test data only after a certain time into the test when radial flow conditions have been established. Test results can also be affected by borehole or formation conditions that do not meet the assumptions of a fully penetrating well in an infinite homogeneous and isotropic aquifer.

Criterion 5G of 10 CFR Part 40, Appendix A, also specifies that borehole geologic and geophysical data must be sufficient to identify "significant discontinuities, fractures, and channeled deposits of high hydraulic conductivity." Determining the borehole density that is "sufficient" requires a certain amount of professional judgment. Some rock types, such as limestone, can have widely spaced zones of high hydraulic conductivity. Other rock types would be expected to have relatively uniform hydraulic conductivity.

Criterion 18 - For Title II sites, baseline monitoring must be conducted for at least one year prior to the start of major site construction.

For Title II sites, Criterion 7 of 10 CFR Part 40, Appendix A, requires that baseline monitoring be conducted for at least 1 year prior to the start of major site construction activities. This monitoring program should include testing to determine hydraulic properties, water-level monitoring to establish flow directions and gradients, and chemical sampling to establish groundwater quality. Seasonal variations in groundwater flow should be identified.

Criterion 19 - The uppermost aquifer must be identified.

The groundwater standards pertain specifically to the uppermost aquifer underlying the disposal site. Uppermost aquifer is defined for Title II sites in 10 CFR Part 40, Appendix A, as "the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility's property boundary." For consistency between groundwater protection programs, the NRC staff considers that this definition should be used for inactive disposal sites as well as active sites (NRC 1988).

Detection Monitoring

For Title I sites, the proposed standards in 40 CFR 192.02(a)(4)(b) require implementation of a monitoring plan for the "post-disposal period" to demonstrate that performance of a disposal facility is in accordance with the design. For Title II sites, criterion 7A of 10 CFR Part 40 requires the establishment of a detection monitoring program for groundwater. The detection monitoring program has two purposes: first, to detect leakage of hazardous constituents so that the need to set groundwater protection standards is monitored; second, to provide data needed by the NRC to establish the site-specific groundwater protection standards. Additional requirements for detection monitoring at Title II sites are given in 40 CFR 264.97-264.98. These rules are not specifically cited for Title I sites. However, some of the requirements are applicable on a technical basis.

The following acceptance criterion pertain to the detection monitoring program at both Title I and Title II sites.

Criterion 20 - One or more upgradient wells must be provided to establish background water quality for the uppermost aquifer.

The concentration limits for many hazardous constituents are often based on background concentrations. Therefore, it is critical to establish the background concentration of constituents. This is the concentration expected in groundwater at the site that is unaffected by the disposal facility. The proposed regulations for Title I sites stipulate that background water quality be determined through one or more upgradient wells. For Title II sites, Criterion 7 of 10 CFR Part 40, Appendix A, requires that a detection monitoring program be implemented to set the site-specific groundwater protection standard. This standard is based on background concentrations at the site.

The upgradient well or wells for measuring background concentrations should be completed in a manner that will provide representative hydrochemical data for the uppermost aquifer. At some sites it may be difficult to place a well upgradient from the disposal. This might occur because the disposal is located near a groundwater divide, the gradient in the vicinity of the site is very flat, or the tailings disposal operation has created a "groundwater mound" in the uppermost aquifer. In such cases, it should be demonstrated that background water quality can be established from wells located in the same aquifer far enough from the disposal to avoid influence from any existing groundwater contamination. In cases where the contaminated materials are transported to a new location that has not been affected by prev[illegible]anium extraction operations, the background wate[illegible] might be established at the disposal site before [illegible]ent of the contaminated material. However, upg[illegible]t background wells would still be needed to indicate water quality changes from some source other than the disposal.

Criterion 21 - Analysis parameters for detection monitoring must indicate if any hazardous constituent is released from the disposal facility into the uppermost aquifer.

The constituents or parameters for detection monitoring will be specified by the NRC based on information from DOE or the Title II site operator. Monitoring may be required for each potential hazardous constituent suspected in the tailings. However, indicator parameters or constituents may be used for detection monitoring. These must give a reliable indication of the presence of hazardous constituents [40 CFR 264.98(a)]. In choosing indicator parameters the factors given in 40 CFR 264.98(a) must be considered.

Criterion 22 - An adequate number of detection wells must be located at the point of compliance to detect any release of hazardous constituents from the disposal facility.

The point of compliance is defined as the surface on the downgradient side of the disposal facility and extending down to the bottom of the uppermost aquifer. Monitoring wells for detection of hazardous constituents should be fully screened through the aquifer, or wells at different depths should be provided so that constituents cannot be transported under or over the screened section. The downgradient direction should be based on an accurate characterization of groundwater flow that takes into account possible seasonal changes in flow direction. The wells should be located as close as possible to the disposal facility to allow early detection of hazardous constituents. Spacing of the wells should be adequate to intercept any plumes originating from the disposal facility.

Criterion 23 - Monitoring wells must be designed and constructed so that the concentrations of hazardous constituents in samples will reflect concentrations in the uppermost aquifer.

Certain requirements for monitoring well construction at Title II sites are given in 40 CFR 264.97(c). These requirements are also generally applicable to Title I sites on a technical basis to ensure that samples are representative. Standards for the design and construction of groundwater monitoring wells are given in ASTM D 4448. Standards for RCRA wells are given in the EPA's RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (EPA 1986).

Monitoring wells should be open to a single aquifer so that concentrations of contaminants in samples are not diluted by water from other aquifers intersected by the well. The well must be cased and sealed at the surface to ensure that contaminants from surface runoff do not enter the well. A screen or perforated section of casing is normally required to allow flow into the well. In unconsolidated formations, a sand or gravel pack may be required so the screen, or perforated section, does not become plugged with fines. Materials used in well construction and sampling devices should not adsorb or otherwise attenuate constituents being monitored. Access to monitoring wells should be controlled by some type of locking cap to ensure sample integrity.

Criterion 24 - Detection samples must be collected at least semi-annually.

The NRC will specify the detection sampling frequency in the facility permit for Title II sites or the Technical Evaluation Report for Title I sites. Regulations in 40 CFR 264.98(d) stipulate that the sampling frequency must be at least semi-annually for Title II sites. This minimum requirement may also be applied to Title I sites on a technical basis. More frequent sampling may be required based on groundwater flow conditions, the disposal facility design, and the proximity to important groundwater resources. The frequency should be at least adequate to detect the presence of hazardous constituents before their concentrations exceed the site groundwater standard.

Criterion 25 - Groundwater flow direction and rate must be determined at least annually during the detection monitoring period.

For Title II sites, the determination of groundwater flow direction and rate is required by Criterion 5G(2) of 10 CFR 40, Appendix A, and by 40 CFR 264.98(e). The requirement may also be applied to Title I sites to show that groundwater flow conditions match those predicted in the performance assessment. Water levels in monitoring wells must be measured to establish gradients and flow direction. Hydraulic properties must also be known. The uncertainty in hydraulic property estimates and in measurements of water elevation should be considered and applied to any flow rate predictions.

Criterion 26 - Reasonable quality assurance measures must be planned to assure that detection samples are representative of concentrations in the aquifer.

It should be demonstrated that reasonable precautions will be taken to avoid contamination of wells during drilling and sampling operations. Sample collection, handling, and analysis methods should also minimize the potential for sample contamination. Standard quality assurance procedures including the analysis of blank and spiked samples should be applied. Procedures for sample collection and analysis should be provided or referenced. EPA (1990) gives procedures for collection and analysis of samples.

Criterion 27 - Appropriate statistical methods must be used in determining if a hazardous constituent is present.

The Title II regulations in 40 CFR 264.98(d) require that a sequence of four samples be taken from each background and detection monitoring well. The concentrations of hazardous constituents in background wells and detection wells must be statistically analyzed according to the methods specified in 40 CFR 264.97(h) to determine if there is statistically significant evidence that the hazardous constituent is present in greater than background concentrations.

Possible statistical methods specified in 40 CFR 264.97(h) are listed below.

- Parametric analysis of variance (ANOVA) followed by multiple comparisons procedures: The method must include estimating and testing the contrasts between each detection well's mean concentration and the background mean concentration for each constituent. The Type I error level for multiple comparison procedures cannot be less than 0.05. The Type I error level for comparisons of concentration at a single detection well with the background cannot be less than 0.01.

- ANOVA based on ranks followed by multiple comparisons procedures: The method must include estimating and testing the contrasts between each detection well's median concentration and the background median concentration for each constituent. The Type I error level for multiple comparison procedures cannot be less than 0.05. The Type I error level for comparisons of concentration at a single detection well with the background cannot be less than 0.01.

- A tolerance or prediction interval procedure in which an interval for each constituent is established from the background data, and the concentration of each constituent in each detection well is compared to the upper tolerance or prediction limit: The NRC must agree that the specified tolerance or prediction interval is protective of human health and the environment.

- A control chart approach that gives control limits for each constituent. The NRC must agree that the specified control limits are protective of human health and the environment.

Another method proposed by the site operator may be used if approved by the NRC. Such approval may be given if the alternate method is protective of human health and the environment. The statistical method must be shown to be appropriate for the type of data distribution. If a statistical test based on a normal distribution is not appropriate, the data should be transformed or a distribution-free test should be used.

An analysis result that is very different than the mean (an outlier) may sometimes be observed. This could come from an error in sampling, analysis, or data handling. Such a test result can be disregarded only if it can be documented that an error occurred.

Criterion 28 - For Title I sites, DOE must show that existing groundwater contamination and cleanup activities will not adversely affect groundwater monitoring of the disposal facility.

If DOE proposes to defer cleanup of existing groundwater contamination at a proposed Title I disposal site, they must demonstrate that disposal can proceed independently of cleanup activities. This has a bearing on the detection monitoring program because existing groundwater contamination may make it difficult to detect releases from the disposal facility. In such a case, DOE must characterize existing groundwater contamination and predict its movement to show that monitoring facilities for the disposal facility will not be affected. They must also show that cleanup activities will not adversely affect the ability to monitor the disposal site, for example, by changing groundwater flow directions.

Compliance Monitoring

If hazardous constituents are detected, then Title II regulations in Criterion 7A of 10 CFR Part 40, Appendix A, specify that the site groundwater standard is established and a compliance monitoring program must be implemented. For Title I sites, a clear distinction is not made between detection and compliance monitoring. However, a monitoring program must be established with one objective being to ensure that hazardous constituents do not exceed established concentration limits at the point of compliance. The monitoring program for Title I sites must demonstrate that the disposal facility is performing as designed for at least the first few decades of its operation.

The following acceptance criteria pertain to monitoring required to demonstrate compliance with the performance requirements.

Criterion 29 - The compliance monitoring program must ensure that any statistically significant exceedence of concentration limits at the point of compliance is detected.

Compliance monitoring is required so that the need for corrective action can be identified. In many cases the detection monitoring wells will be used for compliance monitoring. However, additional monitoring wells may be needed to ensure that the maximum concentration area of the plume is monitored at the point of compliance, and not just the fringes of the plume. Requirements for well construction, and for sample handling and analysis procedures, apply to monitoring wells for the compliance monitoring program as well as the detection monitoring program.

Criterion 30 - Compliance monitoring should demonstrate that the disposal facility is operating as designed.

The requirement for demonstrating initial performance of a Title 1 disposal facility implies that the monitoring program must, at a minimum, be able to detect hazardous or radioactive constituents that reach the point of compliance in concentrations greater than the concentration limits. However, because the monitoring period is short in comparison to the designed control period, monitoring at the point of compliance may not be sufficient to demonstrate that the disposal facility is operating as designed, as required by 40 CFR 192.02(b). Monitoring to verify assumptions made in the performance assessment or to verify predictions of seepage rate and contaminant transport may be required. Examples may include the monitoring of moisture seepage through the cover or contaminated materials, and collection of samples from lysimeters to check constituent concentrations in seepage. These facilities may be temporary and may be removed at the end of the compliance monitoring period so that the integrity of the disposal facility is not compromised.

Various types of barriers may be useful in the protection of groundwater resources at some uranium mill tailings disposal sites. Barriers can be classified as physical flow barriers or geochemical barriers. Physical barriers act to impede the flow of seepage or groundwater through a reduction in permeability along the flow path or an induced change in hydraulic gradient. These barriers include liners placed below the contaminated materials, slurry walls, grout curtains, and regions of artificially induced high hydraulic head. Geochemical barriers consist of material placed in the flow path of contaminants that will react with and immobilize hazardous and radioactive constituents.

Physical Barriers

Liners

The following acceptance criteria are related to the need for liners and the design of liner systems at Title I and Title II disposal sites.

Criterion 31 - A liner must be provided for new impoundments or additions to impoundments where the waste materials will contain excess moisture over the specific retention, or it must be demonstrated that an alternate design will provide protection of groundwater and surface water that is at least as effective as the required liner.

For Title I sites, the proposed EPA standards [40 CFR 192.192.20(a)(2)] require a "liner or equivalent to prevent contamination of groundwater" at new disposal sites for tailings that contain water over the specific retention of the material and at sites where tailings are slurried to a new location. The purpose of these rules is clearly to eliminate the drainage of excess liquid from the waste materials.

Residual radioactive materials at Title I processing sites generally do not contain water above the specific retention of the materials. Therefore, even if the tailings are relocated, a liner is generally not required. If water is added for dust control or other purposes when relocating waste, however, it must be demonstrated that the as-built moisture content is less than the specific retention. Otherwise a liner or "equivalent" is required. The equivalent of a liner is not specified. Presumably, this could be a natural low-permeability soil or rock underlying the disposal site. To be equivalent to a liner, the material would have to limit flow from the Title I disposal facility to the degree needed to protect groundwater. The performance assessment would have to show that drainage of residual moisture through the liner or equivalent would not cause regulated constituents in groundwater at the point of compliance to exceed concentration limits during the specified control period.

A liner is required for Title II tailings impoundments by 10 CFR Part 40, Appendix A, Criterion 5A, and by the RCRA regulations in 40 CFR 264.221. Specific requirements for the liner are also given in these regulations.

For Title II sites, the liner system must prevent migration of waste into underlying soil during the designed control period, or it must be demonstrated that an alternate design will prevent the migration of any hazardous constituents into groundwater or surface water at any future time, or it must be demonstrated that an alternate system and operating practices will provide protection of groundwater and surface water that is at least as effective as a liner and leachate collection system. These exceptions to the liner requirement provide flexibility in designing a site-specific disposal facility. Natural conditions and operating practices may be relied on in some cases to provide containment. Such a design would have to be supported by an accurate and defensible analysis of site conditions. Factors to be considered in deciding if an alternate design is acceptable include the nature and quantity of wastes, alternate design, hydrologic setting, attenuative capacity of subsoils between the impoundment and the uppermost aquifer, and all other factors that would influence the migration of hazardous constituents from the impoundment.

Criterion 32 - If a liner is proposed, it must be stable over its design life.

The requirements for Title II sites (10 CFR Part 40, Appendix A, Criterion 5) mandate that the liner must be constructed of materials with appropriate chemical properties and sufficient strength to withstand the expected pressure gradients. Chemical properties of the liner and potential reaction with waste materials should be considered. Construction methods should protect against damage through settlement, compression, or uplift. An adequate base should be provided if needed. The potential for seismic damage should also be considered in the design.

To satisfy the long-term performance requirements for Title I sites [CFR 192.02(a)] and the requirement to minimize maintenance [40 CFR 264.111(a)], DOE must demonstrate that the liner material will continue to be effective for as long as necessary to meet the design requirements. Therefore, essentially the same requirements listed above for Title II sites can be applied on a technical basis.

Other Physical Barriers

Physical barriers such as grout curtains and slurry walls can usually only delay the transport of constituents from the disposal facility. They can force the contaminants to follow a longer flow path, which might provide greater potential for geochemical attenuation. However, because the point of compliance is at the downgradient edge of the area where the waste is placed, these types of barriers are usually not useful for meeting groundwater protection standards. Barriers consisting of areas of high hydraulic head created through injection of water are not acceptable as a long-term remedial action because they rely on maintenance.

Geochemical Barriers

A geochemical barrier placed beneath the contaminated materials in a disposal facility is a possible method for immobilizing hazardous and radioactive constituents before they reach the uppermost aquifer. The geochemical barrier would contain materials that adsorb or react with hazardous and radioactive constituents. For example, a site lacking enough natural neutralization potential might use a geochemical barrier of some material with limestone to neutralize acidic seepage from the tailings and react with constituents to form insoluble solids. Limestone ($CaCO_3$), and hydrated lime ($Ca(OH)_2$) have been studied as neutralizing agents for uranium tailings solution (Opitz et al. 1985).

Criterion 33 - It must be demonstrated that the proposed geochemical barrier is effective in attenuating hazardous and radioactive constituents under the expected geochemical conditions.

If a geochemical barrier is proposed, the burden of proof is on DOE or the Title II site operator to demonstrate, through laboratory bench-scale or field-scale testing that the barrier material will have the attenuating effects assumed by the disposal design. If such a barrier is to replace the normally required liner, it must be shown that the barrier will be at least as effective as a liner and leachate collection system in preventing the migration of hazardous constituents to groundwater.

Criterion 34 - If a geochemical barrier is a part of the disposal design, its reaction or exchange capacity must be sufficient to retard or attenuate transport of hazardous constituents.

DOE or the Title II operator must demonstrate that the mass of materials used in the proposed geochemical barrier will have sufficient capacity to meet the design assumptions for attenuation of hazardous and radioactive constituents. The possibilities of preferential flow paths through the barrier should be considered because these phenomenon may decrease the mass of barrier material contacted by contaminants.

Criterion 35 - Materials used in a geochemical barrier must be compatible with other components of the disposal facility design.

There is a potential for materials used in a geochemical barrier to chemically interact with adjacent cell components. This interaction might reduce the effectiveness of other components such as liners. The interaction with adjacent components might also have an adverse effect on the geochemical barrier. This potential interaction should be considered in the design.

Groundwater Cleanup Programs

In this section, review guidelines are given regarding the efficiency and effectiveness of various approaches to cleanup of contaminated groundwater. For Title I sites, the Remedial Action Plan prepared by DOE should specify the schedule and steps needed for groundwater cleanup. For Title II sites, cleanup of existing contamination may be addressed in the licensing of an ongoing processing operation. Cleanup should also be addressed in planning a corrective action program.

The following acceptance criteria are related to cleanup of existing groundwater contamination:

Criterion 36 - Provisions should be made for verification of the success of groundwater cleanup.

Regardless of the approach taken to clean up existing groundwater contamination, DOE or the Title II operator should commit to the level of monitoring needed to determine the effectiveness of the cleanup program. Criterion 7A of 10 CFR Part 40, Appendix A, requires that a corrective action monitoring program be implemented. The monitoring network may use facilities designed for detection or compliance monitoring where appropriate.

Criterion 37 - If groundwater cleanup is deferred, it must be demonstrated that any planned disposal activities can proceed independently of groundwater cleanup and that public health and safety will not be endangered.

This demonstration should show that the disposal will not preclude future cleanup activities such as placement of wells, and that existing groundwater contamination will not interfere with monitoring of the performance of the planned disposal. It must be possible to distinguish existing contamination reaching the point of compliance from contaminants released from the disposal facility.

It must also be demonstrated that public health and safety will not be endangered by the delay in groundwater cleanup. Normally, such a demonstration involves the identification of any currently used groundwater or surface water resources that may be affected by the existing contamination. If none are found, then the potential for existing contaminated groundwater to reach other water supplies or potential water supplies in the near future should be evaluated.

Pump-and-Treat Programs

One possible cleanup approach is to pump contaminated groundwater from the aquifer, treat it to remove hazardous and radioactive constituents, and then either inject the water back into the aquifer or dispose of it in some other manner. The following acceptance criteria apply to this approach:

Criterion 38 - The hydraulic characterization of the aquifer and design of the proposed withdrawal system must show with reasonable assurance that contaminated groundwater can be "captured" by the proposed withdrawal wells.

For pumping and treatment to be an effective cleanup method, contaminated water must be removed from the aquifer. This is normally accomplished through withdrawal wells, but drain lines or infiltration trenches could be used in cases where the water table is near the surface.

Haley et al. (1991) have evaluated the effectiveness of several ongoing remedial actions using withdrawal and treatment technology. These are mainly designed to cleanup groundwater contaminated with organics at RCRA and CERCLA sites. Factors that might affect the efficiency of a groundwater extraction system include 1) aquifer properties, 2) contaminant sorption and solubility, 3) size of the plume and existence of a source of contaminants, and 4) design of the extraction system. Many of the affected aquifers at designated processing sites display low hydraulic conductivity. Therefore, a large number of wells with relatively low withdrawal rates may be required to remove contaminated groundwater for treatment. Innovative techniques such as directional drilling might be used to increase the effectiveness of withdrawal wells. By drilling horizontally through the aquifer, a single well could be used to withdraw water from a long interval parallel to the direction of contaminant movement. Fewer withdrawal wells would then be required. The depth of completion intervals should correspond with the depths of groundwater contamination in the aquifer. Withdrawal and injection wells should also be placed to retard the migration of contaminants away from the site.

[illegible] The proposed treatment method must be [illegible] in reducing the concentrations of hazardous and radioactive constituents to less than the allowed concentration limits.

Bench- or pilot-scale treatment tests using contaminated groundwater from the site would be acceptable in showing the effectiveness of the proposed treatment methods. Results from sites where treatment methods have been shown to work might also be extrapolated to sites with similar groundwater chemistry and waste characteristics.

Criterion 40 - The effect of injecting treated water (if proposed) on the pattern of groundwater flow in the aquifer must be evaluated.

If treated groundwater is injected into the aquifer it will create mounds in the potentiometric surface and affect groundwater flow directions. An analysis of groundwater flow in the aquifer including the effects of withdrawal and injection should be made to predict the flow of remaining contaminated groundwater. Injection wells could be used to keep contaminated groundwater from migrating away from the site during the remediation period, or to direct the flow of remaining contaminated groundwater toward withdrawal wells.

Accuracy of numerical models used for prediction of flow and transport should be demonstrated and the assumptions used should be realistic and conservative. The misapplication of transport models often gives inaccurate results, especially in situations where several pumping and injecting wells must be simulated. El-Kadi (1988) documents an example of inaccurate results from a transport model misapplied to remedial action situations involving pumping and injection wells.

In Situ Treatment Programs

At some sites, treating contaminated groundwater in the aquifer may be an effective and more cost-efficient method of groundwater cleanup than the pump-and-treat approach. The acidic condition of seepage from most uranium mill tailings results in increased mobility of most hazardous and radioactive constituents. Therefore, simply raising the pH of contaminated groundwater to a near-neutral value may reduce the concentration of contaminants in seepage to less than the applicable concentration limits. Bioremediation may also be useful in the in situ treatment of some constituents.

The following acceptance criteria apply to remedial action plans for groundwater cleanup that propose in situ chemical treatment.

Criterion 41 - Laboratory testing of representative samples must show that the treatment will be effective in reducing constituent concentrations to acceptable levels.

For chemical treatment, laboratory tests should show that mixing proposed treatment reagents with samples of contaminated groundwater under the expected geochemical conditions will result in dissolved constituent concentrations lower than the concentration limits. The effectiveness of any proposed bioremediation must also be demonstrated. If some hazardous constituents remain over acceptable limits following treatment, DOE must provide an additional cleanup step to reduce concentrations of those constituents, or apply for alternate concentration limits.

Numerical models might also be used to predict the equilibrium concentrations of constituents following chemical treatment. Such a model could be applied to a variety of different conditions present in the aquifer, or used to conduct sensitivity studies with different types or concentrations of reagents. However, such models should be verified by laboratory tests.

Criterion 42 - The method of injecting reagents must result in sufficient mixing with contaminated groundwater to make the treatment effective.

For an in situ treatment program to be effective, the injected reagents must make contact with the contaminated groundwater being treated. Because groundwater moves slowly, especially in the relatively low-permeability aquifers at some processing sites, mixing in the aquifer may be difficult to accomplish. Numerical transport models may be used to determine the extent of the influence of injected reagents. Input data for such modeling, including hydraulic properties and dispersivity values, must be shown to be representative. A corrective action monitoring program must be implemented to monitor and evaluate the degree of mixing and the effectiveness of treatment.

Effects of the treatment itself on hydraulic properties should also be considered. For example, if a solid precipitate is formed by the treatment process, the formation of precipitate may result in a significant reduction of the hydraulic conductivity around the injection borehole.

Criterion 43 - The total mass of reagent material proposed must be sufficient to treat the mass of contaminants present in the groundwater.

By calculating the total volume of contaminated groundwater, it should be possible to determine the minimum reagent mass required to treat the mass of contaminants in solution. As stated above, this mass of reagents must also be mixed sufficiently with the groundwater for treatment to be effective. Since mixing efficiency will be less than 100%, a larger mass of reagent will be required.

Criterion 44 - The effectiveness of the treatment must be determined by an adequate monitoring program.

Results of in situ treatment must be verified by collecting and analyzing groundwater samples from an appropriate network of monitoring wells, as described in the section on monitoring programs.

Natural Flushing

In some cases, natural processes might be sufficient to reduce concentrations of hazardous and radioactive constituents in affected groundwater to less than the concentration limits within an allowable period. An active groundwater treatment program would not be necessary. However, because an extended time period would probably be required for these processes, 40 CFR 192.12(c)(4) may have to be invoked to extend the remedial period for Title I sites.

Criterion 45 - If the remedial period is extended to allow cleanup through natural processes, the requirements of 40 CFR 192.12(c)(4) must be met.

To extend the remedial period for groundwater cleanup for up to 100 years at Title I sites, it must be demonstrated that 1) established concentration limits will not be exceeded during the extended period, 2) institutional control will be maintained, 3) the affected groundwater is not now and is not projected to become a source of public drinking water, and 4) contaminated materials will be disposed of in accordance with 40 CFR 192 Subparts A and C within time limits specified by UMTRCA. The requirement that established concentration limits not be exceeded is taken to pertain to groundwater outside the limits of the present contaminated plume. An assessment of plume movement and attenuation is needed to predict future movement of contaminants and demonstrate that this requirement will be met.

Criterion 46 - For cleanup through natural flushing, reasonable assurance must be provided that natural processes will be effective in cleaning up existing groundwater contamination.

Processes that can naturally reduce the concentrations of constituents include dispersion, neutralization/precipitation, and sorption. If natural flushing is selected for groundwater cleanup, then DOE or the site operator must demonstrate that these processes will result in the concentrations of all identified hazardous and radioactive constituents being reduced to less than their established concentration limits. To show that natural flushing and natural attenuation processes will be adequate to protect groundwater, a good understanding is required regarding aquifer geometry, aquifer hydraulic properties, groundwater flow rate, and geochemical properties. This information must be obtained from technically defensible characterization activities. The uncertainties in these parameters must also be considered.

In some situations, delaying the start of an active groundwater restoration program will result in increased eventual costs and difficulty in achieving groundwater cleanup. Advection and dispersion may spread the contaminant plume and not reduce contaminants to acceptable levels. Therefore, natural flushing should not be relied on without a high degree of confidence that it will be effective.

References

Bouwer, H. 1964. "Measuring Horizontal and Vertical Hydraulic Conductivity of Soil with the Double-Tube Method." Soil Sci. Soc. Amer. Proc. 28:19-23.

Bouwer, H. 1966. "Rapid Field Measurement of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis." Water Resour. Res. 2(4):729-738.

Bouwer, H., and R. C. Rice. 1976. "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells." Water Resour. Res. 12(3):423-428.

Bredehoeft, J. D., and S. S. Papadopulos. 1980. "A Method for Determining the Hydraulic Properties of Tight Formations." Water Resour. Res. 16(1):233-238.

Breiner, R. J. III. 1986. "A Review of Quality Control Considerations in Soil Sampling." In Quality Control in Remedial Site Investigations: Hazardous and Industrial Solid Waste Testing, Fifth Volume, ASTM STP 925, ed. C. L. Perket. American Society for Testing and Materials, Philadelphia.

Cooper, H. H., J. D. Bredehoeft, and I. S. Papadopulos. 1967. "Response of a Finite Diameter Well to an Instantaneous Charge of Water." Water Resour. Res. 3(1):263-269.

Cooper, H. H., and C. E. Jacob. 1946. "A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well Field History." Trans. Am. Geophys. Union 27:526-534.

Crank, J. 1956. The Mathematics of Diffusion. Oxford University Press, Oxford, 347 pp.

DOE. 1989. Technical Approach Document - Revision II. UMTRA-DOE 050425.002, U.S. Department of Energy, UMTRA Project Office, Albuquerque, New Mexico.

El-Kadi, A. 1988. "Applying the USGS Mass-Transport Model (MOC) to Remedial Actions by Recovery Wells." Ground Water 26(3):281-288.

EPA. 1986. RCRA Ground-Water Monitoring Technical Enforcement Guidance Document (TEGD). OSWER-9950.1, U.S. Environmental Protection Agency, Washington, D.C.

EPA. 1988. Design, Construction and Evaluation of Clay Liners for Waste Management Facilities. EPA/530-SW-86-007F, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, Ohio.

EPA. 1990. Test Methods for Evaluating Solid Waste, Revision 1. SW-846, U.S. Environmental Protection Agency, Washington, D.C.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

Galkin, N. P., B. N. Sudarikov, U. D. Veryatin, Yu. D. Shishkov, and A. A. Maiorov. 1966. Technology of Uranium. Israel Program for Scientific Translations, Jerusalem.

Glass, R. J., J-Y. Parlange, and T. S. Steenhuis. 1989. "Wetting Front Instability: 1) Theoretical Discussion and Dimensional Analysis." Water Resour. Res. 25(6):1187-1194.

Glass, R. J., J-Y. Parlange, and T. S. Steenhuis. 1990. "Immiscible Displacement in Porous Media: Stability Analysis of Three-Dimensional, Axisymmetric Disturbances With Application to Gravity-Driven Wetting Front Instability." Water Resour. Res. 27(8):1947-1956.

Haji-Djafari, S., P. E. Antommaria, and H. L. Crowse. 1981. "Attenuation of Radionuclides and Toxic Elements by In Situ Soils at a Uranium Tailings Pond in Central Wyoming." In Permeability and Groundwater Contaminant Transport, ASTM STP 746, eds. T. F. Zimmie and C. O. Riggs. American Society for Testing and Materials, Philadelphia.

Haley, J. L., B. Hanson, C. Enfield, and J. Glass. 1991. "Evaluating the Effectiveness of Ground Water Extraction Systems." Ground Water Monitoring Rev., Winter, 1991.

Herzog, B. L., and W. J. Morse. 1986. "Hydraulic Conductivity at a Hazardous Waste Disposal Site: Comparison of Laboratory and Field Measured Values. Waste Manage. 4:177-187.

Horner, D. R. 1951. "Pressure Build-Up in Wells." In Proceedings, Third World Petroleum Congress, Sec. II, pp. 503-523. The Hague, Netherlands.

I.A.E.A. 1987. Safe Management of Wastes from the Mining and Milling of Uranium and Thorium Ores. Safety Series No. 85, International Atomic Energy Agency, Vienna.

Jacob, C. E., and S. W. Lohman. 1952. "Nonsteady Flow to a Well of Constant Drawdown in an Extensive Aquifer." Trans. Am. Geophys. Union 33(4):559-569.

Kahn, A. U., and W. A. Jury. 1990. "A Laboratory Study of the Dispersion Scale Effect in Column Outflow Experiments." J. Contam. Hydrol. 5:119-131.

Miller, C. C., A. B. Dyes, and C. A. Hutchinson, Jr. 1950. "The Estimation [illegible] rmeability and Reservoir Pressure from Bottom Hole Pressure Build-Up Characteristics." Trans. AIME 189:91-104.

NRC. 1988. Information Needs to Demonstrate Compliance with EPA's Proposed Groundwater Protection Standards in 40 CFR Part 192, Subparts A-C. Draft Technical Position (June 1988). U.S. Nuclear Regulatory Commission, Washington, D.C.

NRC. 1989. Standard Format and Content for Documentation of Remedial Action Selection at Title I Uranium Mill Tailings Sites. Staff Technical Position, U.S. Nuclear Regulatory Commission, Washington, D.C.

Opitz, B. E., M. E. Dodson, and R. J. Serne. 1985. Uranium Mill Tailings Neutralization: Contaminant Complexation and Tailings Leaching Studies. NUREG/CR-3906 (PNL-5179), U.S. Nuclear Regulatory Commission, Washington, D.C.

Rogowski, A. S. 1990. Relationship of Laboratory and Field Determined Hydraulic Conductivity in Compacted Layer. EPA/600/2-90/025, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, Ohio.

Shepherd, T. A., and J. A. Cherry. 1980. "Contaminant Migration in Seepage from Uranium Tailings Impoundments: An Overview." In Symposium on Uranium Mill Tailings Management, November 24-25, 1980, Ft. Collins, Colorado, pp. 299-331. Geotechnical Engineering Program, Civil Engineering Department, Colorado State University, Ft. Collins, Colorado.

van Genuchten, M. T., and D. R. Nielsen. 1985. "On Describing and Predicting the Hydraulic Properties of Unsaturated Soils." Ann. Geophys. 3(5):615-628.

APPENDIX

Listing of Acceptance Criteria

Leaching and Long-Term Releases of Hazardous and Radioactive Constituents from Contaminated Materials

Criterion 1: Assumed conditions of cover operation should be realistic and conservative.

Criterion 2: Samples for determining hydraulic and physical properties of the infiltration barrier must be representative.

Criterion 3: The hydraulic conductivity of the infiltration barrier must be based on accepted test methods.

Criterion 4: Site climatic conditions must be characterized well enough to support design and performance assessment calculations of the moisture flux.

Criterion 5: The disposal facility must be designed so that excess moisture will not build up in the contaminated materials.

Criterion 6: Calculations of infiltration rate must be conservative.

Criterion 7: As-built hydraulic properties critical to the performance of the disposal facility should be verified.

Criterion 8: Materials used to limit seepage through the disposal facility must be stable over the design life of the facility.

Criterion 9: All hazardous constituents that are reasonably expected to be in or derived from the residual radioactive material must be identified.

Criterion 10: Concentrations of hazardous constituents expected in seepage must be conservatively determined from pore water samples or from leach tests.

Criterion 11: Samples for determining hazardous constituent concentrations expected in seepage must be representative of the waste materials.

Attenuation of Hazardous and Radioactive Constituents

Criterion 12: The disposal facility must be designed to provide control that is effective for 1000 years, to the extent reasonably achievable, and, in any case, for at least 200 years.

Criterion 13: If mechanical dispersion is important in the performance assessment, dispersivity values must be representative of the porous media.

Criterion 14: Diffusion of constituents should be considered as a possible transport mechanism.

Criterion 15: Geochemical processes assumed to remove constituents or slow transport must be supported by reliable geochemical characterization data.

Criterion 16: If neutralization or ion exchange processes are assumed to slow or remove constituents, it must be demonstrated that sufficient neutralization or exchange capacity exits.

Groundwater Monitoring Programs

Criterion 17: Adequate hydrogeologic information must be provided concerning the soil and geologic formations underlying the proposed disposal site.

Criterion 18: For Title II sites, baseline monitoring must be conducted for at least one year prior to the start of major site construction.

Criterion 19: The uppermost aquifer must be identified.

Criterion 20: One or more upgradient wells must be provided to establish background water quality for the uppermost aquifer.

Criterion 21: Analysis parameters for detection monitoring must indicate if any hazardous constituent is released from the disposal facility into the uppermost aquifer.

Criterion 22: An adequate number of detection wells must be located at the point of compliance to detect any release of hazardous constituents from the disposal facility.

Criterion 23: Monitoring wells must be designed and constructed so that the concentrations of hazardous constituents in samples will reflect concentrations in the uppermost aquifer.

Criterion 24: Detection samples must be collected at least semi-annually.

Criterion 25: Groundwater flow direction and rate must be determined at least annually during the detection monitoring period.

Criterion 26: Reasonable quality assurance measures must be planned to assure that detection samples are representative of concentrations in the aquifer.

Criterion 27: Appropriate statistical methods must be used in determining if a hazardous constituent is present.

Criterion 28: For Title I sites, DOE must show that existing groundwater contamination and cleanup activities will not adversely affect groundwater monitoring of the disposal facility.

Criterion 29: The compliance monitoring program must ensure that any statistically significant exceedence of concentration limits at the point of compliance is detected.

Criterion 30: Compliance monitoring should demonstrate that the disposal facility is operating as designed.

Design and Construction of Groundwater Protection Barriers

Criterion 31: A liner must be provided for new impoundments or additions to impoundments where the waste materials will contain excess moisture over the specific retention, or it must be demonstrated that an alternate design will provide protection of groundwater and surface water that is at least as effective as the required liner.

Criterion 32: If a liner is proposed, it must be stable over its design life.

Criterion 33: It must be demonstrated that the proposed geochemical barrier is effective in attenuating hazardous and radioactive constituents under the expected geochemical conditions.

Criterion 34: If a geochemical barrier is a part of the disposal design, its reaction or exchange capacity must be sufficient to retard or attenuate transport of hazardous constituents.

Criterion 35: Materials used in a geochemical barrier must be compatible with other components of the disposal facility design.

Groundwater Cleanup Programs

Criterion 36: Provisions should be made for verification of the success of groundwater cleanup.

Criterion 37: If groundwater cleanup is deferred, it must be demonstrated that any planned disposal activities can proceed independently of groundwater cleanup and that public health and safety will not be endangered.

Criterion 38: The hydraulic characterization of the aquifer and design of the proposed withdrawal system must show with reasonable assurance that contaminated groundwater can be "captured" by the proposed withdrawal wells.

Criterion 39: The proposed treatment method must be effective in reducing the concentrations of hazardous and radioactive constituents to less than the allowed concentration limits.

Criterion 40: The effect of injecting treated water (if proposed) on the pattern of groundwater flow in the aquifer must be evaluated.

Criterion 41: Laboratory testing of representative samples must show that the treatment will be effective in reducing constituent concentrations to acceptable levels.

Criterion 42: The method of injecting reagents must result in sufficient mixing with contaminated groundwater to make the treatment effective.

Criterion 43: The total mass of reagent material proposed must be sufficient to treat the mass of contaminants present in the groundwater.

Criterion 44: The effectiveness of the treatment must be determined by an adequate monitoring program.

Criterion 45: If the remedial period is extended to allow cleanup through natural processes, the requirements of 40 CFR 192.12(c)(4) must be met.

Criterion 46: For cleanup through natural flushing, reasonable assurance must be provided that natural processes will be effective in cleaning up existing groundwater contamination.

Distribution

No. of
Copies

OFFSITE

6 U.S. Nuclear Regulatory Commission

M. Fliegel
Division of Low-Level Waste Management
and Decommissioning
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
55111 Rockville Pike
Rockville, MD 20852

D. Gillen
Division of Low-Level Waste Management
and Decommissioning
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
55111 Rockville Pike
Rockville, MD 20852

L. Hamdan
Division of Low-Level Waste Management
and Decommissioning
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
55111 Rockville Pike
Rockville, MD 20852

M. Layton
Division of Low-Level Waste Management
and Decommissioning
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
55111 Rockville Pike
Rockville, MD 20852

No. of
Copies

M. Thaggard
Division of Low-Level Waste Management
and Decommissioning
Office of Nuclear Material Safety
and Safeguards
U.S. Nuclear Regulatory Commission
55111 Rockville Pike
Rockville, MD 20852

NRC Document Control Center
MS P1-37
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

ONSITE

17 Pacific Northwest Laboratory

R. W. Bryce
P. G. Doctor
J. M. Gephart
R. L. Moffitt
F. A. Spane
P. D. Thorne (5)
Publishing Coordination
Technical Files (5)

Routing

R. M. Ecker
J. W. Falco
M. J. Graham
R. L. Skaggs
P. C. Hays (last)

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)
NUREG/CR-5858
PNL-7986

2. TITLE AND SUBTITLE
Information for Consideration in Reviewing Groundwater Protection Plans for Uranium Mill Tailings Sites

3. DATE REPORT PUBLISHED
MONTH: May YEAR: 1992

4. FIN OR GRANT NUMBER
L1411

5. AUTHOR(S)
P. D. Thorne

6. TYPE OF REPORT
Technical

7. PERIOD COVERED (Inclusive Dates)
July 1990 - March 1992

8. PERFORMING ORGANIZATION – NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)
Pacific Northwest Laboratory
Richland, WA 99352

9. SPONSORING ORGANIZATION – NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)
Division of Low-Level Waste Management and Decommissioning
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

Guidelines and acceptance criteria were developed for reviewing certain aspects of groundwater protection plans for uranium mill tailings sites. The aspects covered include 1) leaching and long-term releases of hazardous and radioactive constituents from tailings and other contaminated materials, 2) attenuation of hazardous and radioactive constituents in groundwater under saturated and unsaturated conditions, 3) design and implementation of groundwater monitoring programs, 4) design and construction of groundwater protection barriers, and 5) efficiency and effectiveness of groundwater cleanup programs. The objective of these guidelines is to assist the U.S. Nuclear Regulatory Commission staff in reviewing remedial action plans for inactive waste sites and licensing application documents for active commercial uranium and thorium mills.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)
uranium mill tailings, groundwater

13. AVAILABILITY STATEMENT
Unlimited

14. SECURITY CLASSIFICATION
(This Page) Unclassified
(This Report) Unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

FIRST CLASS MAIL
POSTAGE AND FEES PAID
USNRC
PERMIT NO. G-67