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Technology Assessment Guide for Application of Engineered Sorbent Barriers to Low-Level Radioactive Waste Disposal Sites

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June 1989

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TECHNOLOGY ASSESSMENT GUIDE FOR
APPLICATION OF ENGINEERED SORBENT
BARRIERS TO LOW-LEVEL RADIOACTIVE
WASTE DISPOSAL SITES

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SUMMARY

An engineered sorbent barrier (ESB) uses sorbent materials (such as activated carbon or natural zeolites) to restrict migration of radionuclides from low-level waste sites. The permeability of the ESB allows moisture to pass while the sorbent material traps or adsorbs contaminants. In contrast, waste sites with impermeable barriers could fill with water, especially those waste sites in humid climates.

A sorbent barrier can be a simple, effective, and inexpensive method for restricting radionuclide migration. This report provides information and references to be used in assessing the sorbent barrier technology for low-level waste disposal. The ESB assessment is based on sorbent material and soil properties, site conditions, and waste properties and inventories. These data are used to estimate the thickness of the barrier needed to meet all performance requirements for the waste site. This document addresses the following areas: 1) site information required to assess the need and overall performance of a sorbent barrier; 2) selection and testing of sorbent materials and underlying soils; 3) use of radionuclide transport models to estimate the required barrier thickness and long-term performance under a variety of site conditions; 4) general considerations for construction and quality assurance; and 5) cost estimates for applying the barrier.

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1.0 INTRODUCTION

The Engineered Sorbent Barrier (ESB) technology was developed by Pacific Northwest Laboratory (PNL)^(a) as part of the Low-Level Waste Management Program, sponsored by the U.S. Department of Energy (DOE). During the program, a number of sorbent materials were evaluated and laboratory studies conducted to develop an effective method to limit radionuclide migration from low-level waste (LLW) sites (Freeman, Mitchell, and Buelt 1986; Jones and Freeman 1988). The studies showed that applying an ESB to a particular site must take into account specific site conditions. This technology assessment guide outlines the information that must be considered when designing and constructing an ESB. However, additional information may be required from larger-scale tests before the technology can be applied on a full scale.

Engineered sorbent barriers can be used to restrict relatively short-lived radionuclides such as ^{90}Sr , ^{137}Cs , and ^{60}Co from migrating to the aquifer from LLW burial sites. The barrier is created by lining the bottom of a shallow land burial (SLB) trench or surrounding a vault with sorptive materials such as activated carbon or natural zeolites. Unlike impermeable barriers, ESBs can be designed to allow moisture to pass while selectively sorbing contaminants.

At the present time, a typical design for a humid LLW site would include an impermeable trench cap and liner. Under ideal conditions, the trench cap will limit infiltration of water into the waste. However, if the waste is not completely stabilized, partial failure of the trench cap is likely to occur over the several-hundred-year period that the wastes remain hazardous, allowing water to infiltrate into the waste.

The typical barrier design can be modified to include a sorbent barrier instead of an impermeable liner on the bottom of the trench, as shown in Figure 1.1. The sorbent barrier will adsorb any radionuclide leached from the waste by infiltrating water. Since the sorbent barrier layer is supported by compacted native soil, it is not likely to fail like the trench

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

FIGURE 1.1. Conceptual Design of a Sorbent Barrier Used in a Shallow Land Burial Trench

cap. In addition, since the sorbent barrier is designed to allow infiltrating water to pass, the trench will not fill with water ("bathtub effect"). In contrast, the only way to ensure that the bathtub effect does not occur when using an impermeable liner is through the use of active measures such as a leachate collection system. These systems would not be useful after the loss of institutional control (100 years after closure).

An ESB is designed to prevent the trenches from overflowing while retarding radionuclides sufficiently to ensure that the aquifer at the site boundary does not exceed the drinking water standards mandated by the U.S. Environmental Protection Agency (EPA) in 40 CFR 141. The sorptive behavior of the barrier materials is similar to the ion-exchange properties possessed by many soils for certain radionuclides, except that for soils, the degree of sorption depends on the soil itself, specific radionuclides, and the presence of competing ions and organics. In many cases, the appropriate soils are not indigenous to the site, and/or the radionuclides form mobile complexants.

Work conducted at PNL has shown that ESBs can be constructed using existing procedures and equipment for trenches (Jones and Freeman 1988). Furthermore, the ESBs are free of maintenance after closure. While sorbent barriers are used in conjunction with underlying soils, the sorptive properties of the soils need not be a factor in meeting the DOE 5820.2A criterion of 25 mRem/yr at the site boundary (DOE 1988). (NOTE: This DOE Order is cited in this report as an example regulations that apply to DOE disposal sites.)

A preliminary economic analysis has indicated that applying sorbent barriers in an SLB operation would increase the overall disposal costs by only 1% to 21%, depending on the site (Freeman 1987). In contrast, the cost of a double leachate/liner trench or the use of containment structures is estimated to be several times the cost of current SLB techniques.

Engineered sorbent barriers can be applied to many types of LLW sites because of the flexibility of the design and the properties of the materials. The technology may be used, alone or in combination, in several ways:

- primary barrier for LLW disposal
- backup layer within leachate/liner trench
- backfill around vaults above and below ground
- top cover to prevent contaminant uptake by vegetation.

While originally developed for SLB operations, the barriers can be used for engineered structures or deeper disposal. By adding sorbent materials to the waste itself, the radionuclides could be more tightly bound in the waste form.

Designing a sorbent barrier is similar to designing a standard SLB trench with the added step of estimating the required thickness and hydraulic conductivity of the sorbent barrier layer. The required thickness will depend on the effectiveness of the barrier formulation in sorbing the ions of interest and the conditions that exist at the site. The hydraulic conductivity of the barrier may need to be modified to optimize the leachate residence time in the barrier while still allowing percolation rates that will prevent the trench from filling with water. Keeping the hydraulic conductivities as low as possible also allows the barrier to remain in a near-saturated condition, which is desirable in terms of providing a favorable environment for sorption to take place. A number of parameters pertaining to the site and waste characteristics must be known before the sorbent barrier materials and thicknesses can be determined.

This report outlines the general information necessary to evaluate the technology early in the design phase of the waste site. The text is divided into several sections reflecting the steps involved in choosing LLW sites and formulating sorbent barriers (see Figure 1.2):

- Development of Quality Assurance/Quality Control (QA/QC) Plan
- Site Selection and Characterization
- Projection of Waste Inventories and Characteristics
- Sorbent Barrier Design, including material selection and testing, transport and performance modeling, and construction guidelines.

FIGURE 1.2. Flow Diagram for Designing an Engineered Sorbent Barrier

Although complete treatment of each of these steps is beyond the scope of this document, information specific to assessment of sorbent barriers will be discussed and references that cover these subjects in more detail will be cited.

A good reference on designing low-level radioactive waste facilities is "Conceptual Design Report: Alternative Concepts for Low-Level Radioactive Waste Disposal" (Rogers and Associates 1987). This document covers a number of important issues involved in designing an LLW facility including Licensing Requirements, Technical Requirements, Technical Analysis, Design Basis, Technical Approach, and descriptions of a number of disposal methodologies. It is recommended that the reader become familiar with these design concepts before beginning the evaluation of sorbent barriers.

The appendices contain a description and sources of sorbent materials; a method for performing batch contact tests; an example output from the PATHRAE program; and an analysis of the hydrologic performance of sorbent barriers.

FIGURE 1.1. Flow Diagram for Designing an Engineered Sorbent Barrier

2.0 QUALITY ASSURANCE

The first step that should be taken when evaluating disposal technologies is the development of a quality assurance (QA) and quality control (QC) plan. The implementation of such a plan is critical for providing the framework to ensure that the data and methodologies used in evaluating sorbent barriers are valid and defensible. DOE 5820.2A (DOE 1988) requires that American National Standards Institute/American Society of Mechanical Engineers Nuclear Quality Assurance-1 (ANSI/ASME NQA-1) procedures be followed. The NQA-1 procedures provide criteria for developing an acceptable QA/QC Plan. The 18 criteria that must be addressed in the QA/QC plan have been discussed by Hedges (1988). The categories are listed below.

1. Organization
2. Quality Assurance Program
3. Design Control
4. Procurement Document Control
5. Instructions, Procedures, and Drawings
6. Document Control
7. Control of Purchased Items and Services
8. Identification and Controls of Materials, Parts, Samples, and Documents
9. Control of Processes
10. Inspection
11. Test Control
12. Control of Measuring and Test Equipment
13. Handling, Storage, and Shipping
14. Inspection, Test, and Operating Status
15. Control of Nonconforming Items
16. Corrective Actions

17. Quality Assurance Records

18. Audits.

The application of these criteria to develop a QA/QC plan is site specific and therefore will not be discussed in detail in this document. General QA/QC procedures, as they apply to sorbent material evaluation and barrier construction, will be discussed in the appropriate sections.

3.0 SITE SELECTION AND CHARACTERIZATION

Although selection and characterization of a site provides critical information for the evaluation of ESBs, they are very complex subjects that are beyond the scope of this document. This section will outline general considerations and provide references to documents that address these issues in more detail.

3.1 SITE SELECTION

Proposed sites must be carefully selected based on a number of site-specific criteria such as distance to nearest population, sufficient area for waste disposal, depth to the aquifer, topography, geology, soil chemistry, and site hydrology. The general requirements for site selection are outlined in DOE 5820.2A, Chapter III (DOE 1988) and guidance is provided in the "Site Selection Handbook" (Tullis and Reyes 1988). In general, the site should be as far away from a populated area as possible while minimizing the distance the waste must travel from the generator. Usually, an area with a deep water table is desirable since it may result in a longer travel time than an area with a shallow water table. However, this may not be the case if the hydraulic conductivity of the sites differs greatly. Even though a site may have a deeper water table, if the hydraulic conductivity is high, the higher velocity of the vertical water flow may offset any gains in travel time. The depth to the aquifer must be great enough to allow the waste to be buried with at least 5 m of cover as required by 10 CFR 61. The site must be sufficiently level to minimize erosion caused by runoff.

Another way of maximizing the effective travel times of the radionuclides is to select sites with soils that have high distribution coefficients (K_d) for radionuclides of concern. A K_d is a measure of the effectiveness of a material in adsorbing a particular ion from solution. The K_d is the ratio of the ion concentration in the solids to the concentration in the interstitial water at equilibrium:

$$K_d = C_s / C_{sol} \quad (3.1)$$

where K_d = distribution coefficient, cm^3/g

C_s = concentration in solids, $\mu\text{Ci}/\text{g}$

C_{sol} = concentration in solution, $\mu\text{Ci}/\text{cm}^3$.

The K_d varies depending on soil type and chemistry and types of radionuclide and species. For example, K_d s measured on Savannah River soil for ^{90}Sr , ^{137}Cs and, ^{60}Co are 8, 500, and 10, respectively (Hoeffner 1985). If complexing agents such as EDTA are present, which can complex the cobalt, the K_d for the soil will be reduced to near zero.

Selecting a site based on all of the above considerations is obviously a complex task. If a number of sites are being considered, it is strongly recommended that quantified selection criteria be established to allow ranking of each site. An example of the procedures used in the site selection process is given in Cook, Grant, and Towler (1987).

3.2 SITE CHARACTERIZATION

The site characterization provides essential data for preliminary design and performance assessment modeling, which will determine the impact of the waste facility on the surrounding environment. Some of the key parameters pertaining to sorbent barrier design are discussed below and are used in Section 5.2. Guidance on site characterization parameters and methods can be found in the "Site Characterization Handbook" (Tullis and Reyes 1988) and in two NRC publications (NRC 1988 a,b). An example of techniques used for site characterization can be found in Davis et al. (1984).

The site characterization process is necessary to determine the suitability of a site to safely contain the waste. Parameters of primary importance to sorbent barrier design are distance to and variability of the water table, velocity of the water migration in the vadose (unsaturated) and aquifer (saturated) zones, and mixing depth of the aquifer; bulk density, porosity, and K_d s for all radionuclides of concern for the aquifer and vadose zone matrix; density, porosity, and hydraulic conductivity of the cover materials; and annual precipitation at the site. These parameters are primarily used to calculate the ability of the underlying soil to adsorb and dilute any radionuclides that may escape from the waste site.

Of the site parameters listed above, distance and variability of the water table, velocity of the aquifer, retardation factors for the vadose zone, and infiltration rate have the most influence on site performance. All of these parameters affect the travel time of the radionuclides between the waste site and the aquifer. The greater the distance to the water table or the higher the affinity the soil has in sorbing radionuclides, the longer it takes for the solubilized radionuclides to reach the aquifer. The delay in radionuclide transport that is caused by soil adsorption is referred to as the retardation factor, which is determined by the material K_d , density, and porosity.

The retardation factor is expressed as:

$$R_d = 1 + \rho \frac{K_d}{\theta} \quad (3.2)$$

where R_d is the retardation factor (dimensionless), ρ is the bulk density (g/cm^3) of the material, and θ is the volumetric water content (cm^3/cm^3) of the material.

The retardation factor enhances the effective delay time allowing further time for radionuclides to decay before reaching the aquifer. The increase in time delay is directly proportional to R_d or:

$$t' = t(R_d) \quad (3.3)$$

where t' is the effective delay time and t is the normal travel time for the water.

It is obvious from Equations (3.2, 3.3) that soils with a higher K_d are most desirable. This may be a major consideration when selecting sites over a large region where soil types and geology vary widely. When selecting a site over a uniform region, the K_d of the soils may not vary considerably and would not affect the choice of the specific location. The wide range of K_d found in soils is an example where ESB technology may have a role. A site

may have many desirable attributes for LLW disposal but may have a soil with marginal sorption properties. Such a site could be enhanced with the use of a sorbent barrier.

4.0 PROJECTION OF WASTE INVENTORIES AND CHARACTERISTICS

The quantity and chemical composition of the waste must be estimated over the life of the facility to provide source-term data for barrier design and performance assessment. These estimates are made from previous experience and projections of future activities. A comprehensive survey of each generator is the most effective method of obtaining these data. Since the waste form has a major impact on the composition of the water passing through the site, it is necessary to know the chemical characteristics of the waste in detail. One of the parameters of the waste that has not been known with any degree of certainty in the past is the leachability of the waste. A great deal of effort should be invested in examining the mechanisms and degree of leaching of the various waste forms to be disposed of in the site. The degree of leaching of the waste not only determines the amounts and forms of radionuclides being mobilized but also the amounts of other constituents that can have a major impact on how far the radionuclides will migrate away from the leach site.

DOE 5820.2A, Chapter III (DOE 1988) outlines the types of information that must be recorded for all of the waste being disposed of at an LLW disposal site. Important waste form data include physical and chemical characteristics; volume; weight; radionuclide concentrations; and packaging date, package weight, and external volume. Although this information is useful in the day-to-day operations of the facility, it is obviously not available when initially designing the site.

4.0. ESTIMATION OF WASTE CHARACTERISTICS

The quantity and chemical composition of the waste must be estimated over the life of the facility to provide source-term data for barrier design and performance assessment. These estimates are made from previous experience and projections of future activities. A comprehensive survey of each generator is the most effective method of obtaining these data. Since the waste form has a major impact on the composition of the waste passing through the site, it is necessary to know the chemical characteristics of the waste in detail. One of the parameters of the waste that has not been known with any degree of certainty in the past is the leachability of the waste. A great deal of effort should be invested in examining the mechanisms and degree of leaching of the various waste forms to be disposed of at the site. The degree of leaching of the waste not only determines the amount and form of radionuclides being mobilized but also the amount of other constituents that can have a major impact on how the radionuclides will migrate away from the waste site.

DOE 5810.2A, Chapter III (DOE 1985), outlines the types of information that must be recorded for all of the waste being disposed of at an LWR disposal site. Important waste form data include physical and chemical characteristics; volume; weight; radionuclide concentrations and packaging data; package weight; and external volume. Although this information is useful in the day-to-day operation of the facility, it is obviously not available when initially designing the site.

5.0 SORBENT BARRIER DESIGN

Once the site and waste characteristics are estimated, the formulation and design of the ESB can proceed. The steps in designing the barrier include the following activities:

1. selection of candidate sorbent materials based on waste and ground-water chemistry
2. laboratory testing of sorbent materials under expected trench conditions
3. estimation of required barrier composition, hydraulic conductivity, and thickness based on site and waste characteristics, design life, and sorbent material data obtained from laboratory tests
4. estimation of construction and material costs based on trench dimensions and barrier thickness.

5.1 SELECTION AND TESTING OF SORBENT MATERIALS

The sorbent materials selected for an ESB will depend on the chemistry of the leachate resulting from interaction of infiltrating water and the waste forms, as well as relative costs of materials compatible with the site chemistry. The ions that need to be removed will have the most effect on material selection. A material that may be effective in adsorbing ^{90}Sr may not be effective for ^{60}Co . Since LLW sites contain a mixture of radionuclides, the sorbent barrier will most likely be composed of a mixture of materials. To properly formulate these mixtures, the properties of each material must be known separately. The primary parameter used in developing these formulations is the K_d . The K_d is dependent on a number of factors such as pH, presence of competing ions, surface area of solids, and contact time with solids. These factors must be considered when testing materials and developing the barrier formulation.

A number of other properties such as long-term stability and hydraulic conductivity must also be considered when selecting a candidate sorbent material. These properties affect installation procedures and long-term performance. Natural materials such as zeolites and clays have the advantage of long-term stability and mechanical strength. Synthetic materials may also

have potential, but the long-term stability (several hundred years) may not be known. In addition, other material properties such as hydraulic conductivity, water retention, and maximum density will have to be measured to fully assess the overall performance of the site.

Several promising materials have been evaluated during this program using batch contact and flowthrough tests. The materials were evaluated using a leachate composition chosen to be representative of a humid LLW site: 1 $\mu\text{Ci/L}$ each of ^{60}Co , ^{90}Sr , and ^{137}Cs ; 100 ppm Ca; 100 ppm Na; 100 ppm Mg; and 1 ppm EDTA at a pH of 5. Results of these tests are contained in Freeman, Mitchell, and Buelt (1986). A partial list of materials and their K_d s as determined with batch contact tests is presented in Table 5.1. A description of materials to consider, along with a list of manufacturers, is given in Appendix A.

The K_d s of the materials listed in Table 5.1 are meant as a guide only. Properties of natural materials such as clinoptilolite, clays, and glauconite can vary considerably between or, even within, deposits. The K_d s must be measured in the laboratory using leachate compositions expected for the site under consideration. The methods for obtaining K_d s are described in more detail in the following section and in Appendix B.

TABLE 5.1. Distribution Coefficients of Selected Sorbent Materials

Material	K_d , cm^3/g		
	Co	Sr	Cs
Clinoptilolite, CH Deposit	0	1,270	4,830
Clinoptilolite, XY Deposit	0	558	5,140
Greensand (Glauconite)	0	5.9	5,150
Indian Red Pottery Clay	131	15.8	14,700
Bentonite	109	23.6	1,830
A51 Synthetic Zeolite	216	1,720	1,100
Activated Carbon	995	18	25

5.1.1 Material Testing

As discussed above, a number of properties must be known for candidate sorbent materials before an appropriate choice can be made. For most cases, all of the required properties will not be known for the conditions that exist at a particular site. Distribution coefficients, for instance, can be highly dependent on the chemistry of the leachate generated in the waste site. The K_d s measured for one site should not be applied to another site. The lack of site-specific information on sorbent material properties is even more evident when dealing with mixtures of materials. Even if properties are known for a general class of material, they will not necessarily apply to the source of material being used at the waste site. Materials such as clinoptilolite and bentonite can vary considerably within a deposit. Consequently, it is required that tests be performed on candidate materials under conditions expected to be found at the waste site. Existing information, if available, can be useful as a starting point in designing the tests to obtain site-specific properties.

The K_d can be measured by either the batch contact method or the column elution method. Each method has advantages and disadvantages in terms of cost and applicability.

5.1.1.1 Batch Contact Method

In general, batch contact tests are faster, less costly, and easier to perform than column tests. The disadvantages include small sample size and poor representation of actual field conditions. The small sample size makes it difficult to obtain representative measurements of heterogeneous materials. The intimate contact inherent in the batch contact method may not be representative of the plug flow experienced in full-scale conditions. Batch contact tests are ideally suited for screening studies where a large number of tests must be performed. Batch contact tests are also useful for materials with very high K_d s where column tests are not practical because of the long times required for breakthrough to be observed.

The batch contact method involves contacting a small sample of sorbent material and a solution containing the contaminant ions of interest in a container for a period sufficient for adsorption equilibrium to take place. The

mixture should be agitated slightly during the test to ensure intimate contact of the solids and liquid phases. Excessive agitation should be avoided to minimize the breakup of the solids being tested. The amount of material and liquid used in each test is dependent on the facilities available to the tester, the range of K_d s expected for the materials being tested, and the objective of the test. Typically, a small quantity of sorbent material, such as 1 g, is contacted with 100 to 200 mL of solution. Ideally, a large quantity of solids should be tested, especially for heterogeneous materials such as soil and natural zeolites. Larger solids samples, however, require the use of larger volumes of liquid and the associated costs for supplies and waste disposal. When working with radioactive solutions, using larger quantities can result in higher worker exposures and larger quantities of waste that may be difficult to handle and dispose of.

5.1.1.2 Batch Contact Test Design

When running batch contact tests, a number of parameters should be investigated to determine the sensitivity of the K_d to changes in site conditions. The two primary parameters that should be investigated are pH and competing-ion concentration. Another parameter that could be of consequence if column tests are performed later is the contact time (kinetics).

The effectiveness of some sorbent materials can be highly dependent on pH. Therefore, tests should be performed at several pH units on either side of the expected value. These data can then be used in performance assessments of the barrier or the entire site. An example of the effect of pH on Sr adsorption is shown in Figure 5.1.

Competing ions can also have a major effect on the performance of the barrier. Ions such as Ca^{++} , Na^+ , Mg^{++} are most likely present in waste site leachate in mass concentrations many orders of magnitude greater than the radionuclides. These ions potentially can reduce the effectiveness of the barrier by tying up sorption sites that otherwise would be available to adsorb radionuclides. Therefore, it is important to determine how a change in competing ion concentration affects the K_d . This information may be helpful in making sure the waste form and the sorbent barrier are compatible.

FIGURE 5.1. Effect of pH on Sr Adsorption

For instance, the use of a calcium-based grout to solidify waste may reduce the effectiveness of a barrier in sorbing Sr.

Another parameter that could be important is the kinetics of adsorption of radionuclides on the barrier materials. An assumption made when using a K_d in radionuclide retardation calculations is that the reaction between the ions in the liquid and the solid is instantaneous. In fact, it may take several days for equilibrium to be reached under actual conditions, as shown in Figure 5.2. In a properly designed barrier, these slow kinetics are not of much consequence because the flow rates through the barrier are so slow that there is sufficient residence time for equilibrium to be reached. Under the high flow rates encountered in typical column elution tests, the kinetics of adsorption is extremely important. Therefore, if column elution tests are anticipated, the kinetics of adsorption must be ascertained. These tests may show that column elution tests are not practical.

5.1.1.4 Column Elution Tests

In the column elution method, simulated leachate is passed through a column of material; the exiting solution is analyzed; and the exiting concentration ions are plotted as a function of the volume of simulated leachate passed through the column. This method has an advantage over batch contact

FIGURE 5.2. Effect of Contact Time on Sr Adsorption on Clinoptilolite

tests in that a much larger volume of sorbent material can easily be tested, which is especially important for heterogeneous materials and mixtures of materials. Also, flowthrough column tests are more representative of the way leachate flows through the actual barrier. However, column tests can be time-consuming to run if the K_D is very high. In some cases, several thousand pore volumes of leachate would have to be passed through the column before the breakthrough curve could be determined. If adsorption kinetics are slow, the flowrate through the column must be very low, which further increases the amount of time to perform a test and, thus, is very labor-intensive. If no dispersion is encountered in the column (only happens in theory), the breakthrough curve would look like Figure 5.3a. In practice, some dispersion is experienced, which causes the breakthrough curve to look more like Figure 5.3b. The retardation coefficient, R_D , is numerically equivalent to the cumulative number of pore volumes having passed through the column until the output concentration is 50% of the input concentration. Therefore, the number of times that the radionuclide travel time is increased is the R_D of the sorbent material. Once the R_D is known, the K_D can easily be calculated by rearranging Equation (3.2):

$$K_D = (R_D - 1) \cdot \theta / \rho \quad (5.2)$$

FIGURE 5.3. Example Breakthrough Curves for Column Elution Tests

5.1.2 Determining Physical Properties of the Barrier

A number of physical properties of the sorbent barrier layer must be known to aid in the design and installation of the barrier. These properties include the optimum compaction versus moisture relationship, hydraulic conductivity versus water content relationship, and the water content versus capillary pressure head relationship. These relationships are used to determine the optimum moisture content to achieve the desired compaction during barrier installation and to determine hydrologic performance of the barrier. Since these relationships depend on the particle size and mineral makeup of the material, the aforementioned properties should only be measured on the mixture of materials as determined by Section 5.2 instead of the individual components. More detailed descriptions on these relationships and procedures for making the measurements can be found in Freeze and Cherry (1979) and American Society of Agronomy (1986). Examples of some of these relationships can be found in Appendix D.

5.2 ESTIMATING REQUIRED SORBENT BARRIER PARAMETERS

Three major parameters must be determined for the sorbent barrier layer as part of the overall barrier design: barrier composition, thickness, and hydraulic conductivity. The first two parameters are estimated from the sorbent material K_d s, site and waste characteristics, and performance

objectives using analytic equations or numeric performance assessment models. The optimum hydraulic conductivity is estimated from the annual infiltration rate and trench geometry.

5.2.1 Estimating Sorbent Barrier Composition and Thickness

Because LLW sites contain a number of radionuclides with a range of chemical species, it is unlikely that a single material will be effective in adsorbing all radionuclides of concern. Consequently, the ESB must be composed of two or more materials to meet performance objectives. Furthermore, if there are a number of materials under consideration that may adsorb one or more radionuclides to differing degrees, the most cost-effective material should be used if practical. This section describes a methodology for ranking the relative cost effectiveness of materials and determining the relative amounts of materials required for the barrier formulation.

5.2.1.1 Ranking the Cost Effectiveness of Sorbent Materials

The amount of radionuclide that can be adsorbed in an ESB is determined by the mass and K_d of material. Therefore, a useful way of ranking materials is to look at the cost/ K_d ratio. In other words, a material that costs twice as much per kilogram but has a K_d twice as large as another material would be ranked the same as the lower cost material. This ranking system must be tempered with judgment because there may be constraints on the thickness of a barrier. For instance, a very low cost material that had a low K_d may rank the same as a higher cost, larger K_d material. However, it may take several meters of the lower cost material to meet the performance objectives. The added expense of digging the trench significantly deeper and the lowering of the trench bottom closer to the water table may not be cost effective or advisable. Only a complete system analysis can determine the most suitable material.

5.2.1.2 Calculating the Barrier Composition and Thickness

The composition and thickness of the sorbent barrier will be determined by the site conditions, radionuclide inventory and leachability, performance objectives, and K_d s of the sorbent materials. The barrier composition and thickness must be estimated together since the two parameters cannot be

determined independently. A barrier may meet performance objectives by having a higher concentration of sorbent material in a thinner barrier or by using lower concentrations in a thicker barrier. In most cases it is advantageous to have as high a concentration of sorbent material as possible in the barrier to minimize the barrier thickness. However, when several materials must be used in a barrier, there are limitations on the concentration of any one component. In general, the radionuclide that results in the highest dose at the point of concern should be considered first.

Before the composition and thickness of the barrier can be calculated, the performance of the site without a sorbent barrier must be known unless the intent of using the sorbent barrier is to not rely on the natural environment to restrict migration of the radionuclides. The doses at the point of environmental contact can be calculated using analytic equations or more sophisticated numeric models if desired. The use of simpler models is recommended because the design process is iterative in nature and may require a large number of runs to determine the final design. Furthermore, the large amount of data required for input to more sophisticated models is not easily obtained. Use of analytic equations will minimize the time and resources required to conduct this task. One model that can easily be run on an IBM PC® or compatible is the PATHRAE code developed for EPA (Rogers and Hung 1987). This code can estimate the maximum dose for a number of pathways for any radionuclide for which there is data for input into the data files. For this analysis it is recommended that only the well drinking water pathway be considered since it will be the dominant pathway for a closed SLB site using ESB technology. The site characteristics must be entered into the appropriate PATHRAE data files as outlined in the users manual. Table 5.2 lists recommended values to use for the initial PATHRAE run to establish the benchmark performance assessment.

The output of the PATHRAE run will be a list of pertinent input parameters followed by the maximum dose for each radionuclide, sum of the maximum

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TABLE 5.2. Recommended PATHRAE Parameters to Use for Benchmark Performance Assessment

Variable	Value	Comments
IFILL	1	Start filling trench from downstream end (most conservative estimate).
IOPT	1	Activate peak dose finding routine.
IFLAG	0	Calculate radionuclide inventory at designated times from initial inventory.
INPRINT	1	Print a summary of the input parameters.
NNP	1	Consider only one pathway.
NPN	2	Consider only the groundwater to well pathway.
JUF	1	Consider all types of water use.
XW	1	Assume the well is 1 m downstream of waste site (intruder scenario).

doses for all radionuclides, sum of the risks for all radionuclides, dispersion correction factors for each radionuclide, and peak concentration and time of peak for each radionuclide. An example of this output is shown in Appendix C. The information of interest from this output is the maximum dose and time of peak concentration for each radionuclide of interest. Radionuclides with insignificant maximum doses (<0.1 mRem/yr) can be excluded from further consideration unless there is a large number of these radionuclides being considered. The remaining radionuclides must be analyzed individually with additional PATHRAE runs and analytic calculations as outlined below.

1. Rerun the PATHRAE code using the time of peak concentration for the radionuclide under consideration. The following variables in the appropriate data files must be changed: IOPT = 0, NTIME = 2, T(1) = 1, T(2) = Peak Time. If the input summary listing is not desired the print flag INPRINT can be set to 0. This run will give doses for all radionuclides at the time of peak concentration of the radionuclide under consideration.
2. Sum the doses of all radionuclides except the one under consideration. If this dose is greater than the performance objective assume that the sum of the doses will be half of the performance objective through the use of sorbent materials. This assumption will have to be checked later in the design process. Subtract the

doses of all other radionuclides from the performance objective value. This will be the dose the sorbent barrier will be designed to achieve for the radionuclide under consideration.

3. Divide the dose for the radionuclide under consideration obtained from the benchmark run by the dose obtained from Step 2 to obtain the required reduction factor, RF.
4. Calculate the delay time required to obtain RF from the following equation:

$$DT = -\ln \left(\frac{1}{RF} \right) / \lambda \quad (5.3)$$

where DT = delay time, yr

ln() = natural log

λ = decay constant for radionuclide under consideration, yr⁻¹.

5. Calculate the sorbent barrier properties necessary to obtain required delay time from the following equation:

$$R_d = \frac{(DT)v}{x} \quad (5.4)$$

where R_d = retardation coefficient

x = thickness of barrier, m

$v = \frac{\text{Infiltration Rate}}{\theta}$ = velocity of leachate through barrier, m/yr.

If there is a design criterion that specifies the desired barrier thickness, this value can be input into the equation to obtain the required R_d . If there is no target thickness assume $x = 1$ to provide a lumped $R_d \cdot x$ parameter, RDX, that can be used later to prioritize composition calculations.

6. Repeat Steps 1 through 5 for each radionuclide identified as being significant in the benchmark performance assessment calculation.
7. If the barrier thickness has been specified, the following steps can be used to determine the barrier composition.

- 7a. Calculate the required K_d from Equation (5.2), $K_d = (R_d - 1) \cdot \theta / \rho$. The volumetric water content (θ) and density (ρ) terms refer to the barrier mixture and hence will have to be estimated from the properties of the dominant barrier component.
- 7b. Assume that the effective K_d of the barrier is equivalent to the K_d of the pure component multiplied by the weight fraction of the component in the barrier. The required weight fraction of the component can then be calculated as:

$$w = K_{d\text{req}} / K_{d\text{pure}} \quad (5.5)$$

where w = weight fraction of sorbent material in barrier

$K_{d\text{req}}$ = required K_d as calculated in Step 7a, cm^3/g

$K_{d\text{pure}}$ = K_d of pure sorbent material, cm^3/g .

- 7c. Repeat Step 7b for each radionuclide of interest using the K_d for the optimum sorbent material for that radionuclide.
- 7d. Sum the weight fractions of all of the components used in the barrier. If one sorbent material is used for more than one radionuclide, only use the highest weight fraction in this sum. If the sum of the weight fractions is less than 1, the barrier thickness can be less than the specified value. Alternatively, the barrier can be brought up to the desired thickness by including native soil as the remainder of the weight fraction for the barrier. If the sum of the weight fractions is greater than 1, either a thicker barrier or sorbent materials with higher K_d s must be used.
8. If the barrier thickness has not been specified the steps below should be followed.
- 8a. Rank the RDX parameters obtained in Step 5 for each radionuclide by dividing RDX by the K_d of the sorbent material to be used for that particular radionuclide. This will indicate which radionuclide will require the largest weight fraction and/or barrier thickness to meet performance objectives.
- 8b. Start with the radionuclide that has the highest ranking from Step 8a and assume that the barrier will contain 75% of the sorbent material for that radionuclide. If it is obvious from the ranking in Step 8a that this particular radionuclide dominates the analysis, a higher weight fraction can be assumed. Calculate the required barrier thickness from:

$$x = \text{RDX} / (1 + (w \cdot K_{d\text{pure}} \cdot \rho) / \theta) \quad (5.6)$$

- 8c. Proceed to the next radionuclide on the ranking list from Step 8a and calculate the required K_d from RDX:

$$K_{dreq} = [(RDX/x) - 1] \cdot \theta / \rho \quad (5.7)$$

- 8d. Use Equation (5.4) to calculate the required weight fraction of that sorbent material.
- 8e. Repeat Steps 8c and 8d for each radionuclide in the ranking list in the order of ranking. If a sorbent material has been used for a previously analyzed radionuclide, skip to the next radionuclide on the list.
- 8f. Sum the weight fractions for all of the components of the barrier calculated in Step 8e. If the sum of the fractions is less than 1, the weight fraction for the sorbent material required for the prominent radionuclide in Step 8b can be increased to obtain a smaller sorbent barrier thickness. Repeat Steps 8c through 8f until the weight fractions for all of the components equal 1. Likewise, if the sum of the weight fractions is greater than 1, decrease the weight fraction in Step 8b and repeat Steps 8c through 8f until the weight fractions equal 1.

5.2.2 Estimating Required Barrier Hydraulic Conductivity

One of the key features of sorbent barrier technology is that it is designed to prevent the bathtub effect commonly encountered at humid sites. Hence, the barrier must be permeable to the flow of water but not too permeable or the leachate residence time may not be sufficient to effectively adsorb the contaminants. On the other hand, if the barrier is not permeable enough, the trench could fill with water. The optimum hydraulic conductivity, then, allows the maximum annual infiltration rate to pass through the barrier over a period of a year. This would provide the maximum residence time in the barrier, yet the bathtub effect would not occur.

The calculation of water transport in multilayered unsaturated media is a complex task requiring sophisticated numerical models. To provide a less complex model here, an equation was derived based on trench geometry and mass balance considerations. This equation is intended to provide a conservative estimate of the required hydraulic conductivity:

$$K_{SB} \approx \frac{L_4 q_{INF}}{L_4 + d} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right] \quad (5.8)$$

where K_{SB} = minimum hydraulic conductivity, m/yr

q_{INF} = infiltration rate into trench surface, m/yr

d = saturated thickness of the gravel

L_1 = thickness of soil layer overlying waste containers, m

L_2 = total thickness of waste region, m

L_3 = thickness of gravel layer underlying waste containers, m

L_4 = thickness of sorbent barrier, m

M = slope of trench wall, vertical/horizontal

w_1 = half width of trench bottom, m.

Equation (5.8) was compared with one-dimensional moisture transport simulations using the unsaturated water transport code UNSAT2 (Davis and Newman 1983) to verify that it was indeed conservative. When calculating the required hydraulic conductivity it is better to err on the high side (conservative) and allow higher transmission rates through the barrier than to err on the low side and end up with a saturated trench.

The derivation and comparison of Equation (5.8) with UNSAT2 is presented in Appendix D. The required barrier hydraulic conductivity can be calculated from Equation (5.8) if the trench geometry and annual infiltration rate are known. The various dimensions referred to in the equation are depicted in Figure 5.4.

One of the components of the ESB design in Figure 5.4 is a gravel layer placed directly on the surface of the sorbent barrier layer. This gravel layer serves two main purposes. It provides a relatively dry surface on which to stack waste containers during filling of the trench, and it provides a storage or buffer zone to allow buildup of water during years of high infiltration while minimizing the time the containers are subjected to saturated conditions. It also allows for uniform infiltration into the sorbent barrier. It is recommended that this layer be designed to allow storage of

FIGURE 5.4. Cross-Sectional View of SLB Trench Showing Dimensions Used in Equation (5.8)

twice the average annual infiltration rate, since this amount generally exceeds the 100-year maximum for most sites. The required gravel thickness can be calculated by:

$$L_3 = (2 \cdot q_{INF}) / P \quad (5.9)$$

where P is the porosity of the gravel layer.

Equation (5.8) assumes that all of the water entering through the top of the trench exits through the bottom of the trench. For a given area at the bottom of the trench, a trench with shallow sloping sidewalls will intercept more infiltrate than a trench with steeper sidewalls. Hence, a trench with shallow sloping sidewalls will have a greater volume of water passing through the bottom. Trenches with steep sidewalls will increase the residence time of the leachate in the barrier and increase the amount of land available for other uses, but may make construction of the barrier more difficult.

5.2.3 Performance Assessment of the Barrier System

Once the barrier composition, thickness, and configuration have been determined from the previous sections, the entire system must be assessed in greater detail to provide sufficient documentation to satisfy local, state and federal regulatory agencies. There are a number of performance assessment models available to perform the required analysis; these models have been reviewed elsewhere (Case and Otis 1987; DOE 1985; EG&G 1987; Liebetrau 1987; Mills and Vogt 1983; Mills, Vogt, and Mann 1983; SAIC 1981; and Smith and Cohen 1980).

The selection of the proper performance assessment model will be left to the user based on the requirements of all agencies involved and personal preferences. However, a list of the desired attributes of a performance assessment model that relate to assessment of the sorbent barrier is given below.

1. The model should allow multiple layers to be modeled with respect to water transport and radionuclide migration. At a minimum, the layers should include the surface cover, waste layer, gravel layer, sorbent barrier layer, unsaturated zone, and aquifer.
2. Two- or three-dimensional transport capabilities would be useful in assessing water flow in the barrier system and the spreading of contaminant that may result in the unsaturated and aquifer zones.
3. Use empirical leaching models or coupling to other geochemistry models to calculate time-dependent concentration and speciation of radionuclides and competing ions being leached from the waste forms. If leachate chemistry data are known, adjustments to the soil and barrier K_d s in the transport models can be made.

Results of the detailed performance assessment may show that the barrier system, as originally designed, does not meet the design requirements or is overly conservative in specifying the barrier thickness. If this is the case appropriate adjustments will have to be made by adjusting the barrier thickness or composition in the detailed performance assessment model. The equations used in the original barrier design are conservative and should result in a thicker barrier than actually required. This conservatism provides a

factor of safety in the design. If additional safety is desired, the performance objectives used in the barrier design can be made more stringent than required by applicable regulations.

5.3 CONSTRUCTION GUIDELINES FOR ESB TRENCHES

Another attractive feature of ESBs is that they can be installed using existing equipment and techniques. The optimum technique for installing the sorbent barrier layer is not known at this time but can be determined by constructing test plots using full-scale equipment. The rest of the trench construction will follow existing practices for installing SLB trenches and clay liners and caps. Since these subjects are covered in detail in "Design, Construction and Evaluation of Clay Liners for Waste Management Facilities" (EPA 1986), "Minimum Technology Guidance on Final Covers for Landfills and Surface Impoundments" (cited in EPA 1988), and "Construction Quality Assurance for Hazardous Waste Land Disposal Facilities" (Northiem and Truesdale 1986), this section will only highlight the salient points that should be considered when planning construction of an ESB.

The primary steps in constructing an ESB are 1) trench excavation and preparation; 2) installation of the ESB layer; 3) installation of the side wall liners; 4) installation of the gravel layer; 5) emplacement of the waste containers; 6) stabilization and backfilling of the trench; and 7) installation of the clay cap and soil cover. These steps are briefly described below.

5.3.1 Trench Excavation and Preparation

The first step is to excavate the trench to the design dimensions by using equipment suitable for the site. The trench bottom and walls are then proof-rolled with heavy equipment to detect any soft areas. Depressions are filled, and the surface is smoothed and compacted before a final proof-roll is performed. Density of the compacted surface shall be tested using non-destructive methods such as a nuclear density meter combined with other procedures, e.g., sand cone techniques, as a check on the nuclear methods.

5.3.2 Sorbent Barrier Installation

The sorbent barrier will most likely be composed of several components, which must be mixed before or during application. Possible methods of mixing the materials include batch methods, such as pugmills or rotary mixers, and in situ methods, such as rototilling or discing. This is an area that will require testing with full-scale equipment to determine the quality and uniformity of the barrier as a function of installation techniques. A complete QA program will be required to ensure that the materials meet specification and are properly mixed and placed in the trench. The ESB should be tested for compaction, moisture content, thickness, composition, and hydraulic conductivity at a number of randomly selected locations as determined by the QA/QC plan. Nondestructive testing methods should be used when possible to avoid creating defects in the ESB layer.

5.3.3 Trench Liner Installation

The walls of the trench shall be lined with an impermeable material such as a bentonite/soil mixture or properly sized natural zeolite to ensure that any infiltrating water will be diverted down the trench walls and through the sorbent layer. The installation and QA/QC procedures outlined in EPA (1986) and Northiem and Truesdale (1986) should be followed to ensure that the liner will perform as designed. Careful attention should be paid to the butt joint between the liner and the ESB to ensure that a preferential path for moisture seepage is not created.

5.3.4 Gravel Layer Installation

The purpose of the gravel layer is to provide a dry surface to stack waste containers, store excess moisture infiltration during higher than normal rainfall events, and evenly distribute leachate across the barrier to prevent saturating a small area of the barrier where preferential infiltration may occur. The gravel layer is simply placed in the bottom of the trench to the specified design depth. Caution should be exercised when placing the gravel in the trench bottom to prevent disturbance of the sorbent layer. A thin sand layer over the sorbent barrier can be used to protect the ESB.

5.3.5 Waste Emplacement and Stabilization

The waste containers should be stacked in the trench in the most space-efficient manner possible. Typically, 1.3 m x 1.3 m x 2.3 m steel waste boxes can be stacked on edge, three high. Enough depth must be left in the trench to allow a cover of 5 m to be placed over the waste form. During stacking, consideration should be given to the loading characteristics (e.g., compaction and compressibility) of the host soil and the ESB.

When a section of the trench is full it should be backfilled with soil to a level sufficient to accommodate the cap and soil cover. Depending on the particular situation, a grout may be used to help stabilize the waste forms before or in place of backfilling with soil.

5.3.6 Closure of the Trench

Once the trench has been filled, it must be capped and covered to restrict infiltration of water and discourage human and animal intrusion into the waste form. The use of a clay cap is recommended for infiltration control, while the use of a thick soil cover will help isolate the waste from human and animal intrusion. Guidance on constructing clay caps can be found in EPA (1988).

5.3.7 ESB Trench Construction Cost

The cost of constructing an ESB trench will be site specific, much like the site characterization. The type of groundcover, soil type and conditions, trench dimensions and slope, distance to borrow area, cost of borrow and adsorbent material, and type of equipment used are some of the elements affecting the trench cost. The overall procedure is to estimate the amount of material to be excavated and filled, the type of equipment that will be used, and the man-hours required to complete the work. The volume of material to be excavated and filled is determined from the design drawings. The trench slope and dimensions affect the type of equipment to be used as well as the availability of equipment in the area and the accepted method of spreading and compacting the layers. The number of man-hours is often estimated using the depth and area of the trench.

The most recent editions of Means Building Construction Cost Data 1985 (Godfrey 1984); Dodge Guide to Public Works and Heavy Construction Costs (McMahon 1984); and Process Plant Construction Estimating Standards (Richardson Engineering Services 1983) outline the elements that should be considered. A cost estimator familiar with local costs should be consulted to provide more accurate estimates.

6.0 REFERENCES

American Society of Agronomy. 1986. Methods of Soil Analysis. Monograph No. 9, Part I. 2nd ed.

Case, M. J., and M. D. Otis. 1987. "DOE Performance Assessment Guidance." In Proc. Ninth Annual Participants' Information Meeting on DOE Low-Level Waste Management Program. CONF-870859, Technical Session III, pp 1-11 Denver.

Cook, J. R., M. W. Grant, and O. O. Towler. 1987. New Low-Level Radioactive Waste Storage/Disposal Facilities at the Savannah River Plant. DPST-85-862, Savannah River Laboratory, Aiken, South Carolina.

Davis, E. C., et al. 1984. Site Characterization Techniques Used at a Low-Level Waste Shallow Land Burial Field Demonstration Facility. ORNL/TM-9146, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Davis, L. A., and S. P. Neuman. 1983. Documentation and User's Guide: UNSAT2--Variably Saturated Flow Model. NUREG/CR-3390, U.S. Nuclear Regulatory Commission, Washington, D.C.

EG&G Idaho, Inc. 1987. Guidance for Conduct of Waste Management Systems Performance Assessment. DOE/LLW-63T, U.S. Department of Energy, Washington, D.C.

Freeman, H. D. 1987. "Economic Analysis of Engineered Sorbent Barrier Technology." In Proceedings of the Ninth Annual DOE Low-Level Radioactive Waste Management Conference. CONF-870859-17, August 25-27, 1987, Denver.

Freeman, H. D., S. J. Mitchell, and J. L. Buelt. 1986. Engineered Sorbent Barriers for Low-Level Waste Disposal. PNL-6051, Pacific Northwest Laboratory, Richland, Washington.

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

Godfrey, R. S., ed. 1984. Building Construction Cost Data 1985. 43rd edition. Robert Snow Means Company, Inc., Kingston, Massachusetts.

Hedges, D. 1988. "How Does One Develop the 'Right' Quality Assurance Program for Waste Management Practices." In Proceedings of the 10th Annual DOE Low-Level Waste Management Conference. CONF-880839-Ses. V, August 30-September 1, 1988, Denver.

Hoeffner, S. L. 1985. Radionuclide Sorption on Savannah River Plant Burial Ground Soil - A Summary and Interpretation of Laboratory Data. DP-1702, E.I. du Pont de Nemours and Co., Aiken, South Carolina.

Jones, E. O., and H. D. Freeman. 1988. "Design of Engineered Sorbent Barriers." In Proceedings of the 10th Annual DOE Low-Level Waste Management Conference. CONF-880839, August 30-September 1, 1988, Denver.

Liebetrau, A. M. 1987. "The Adaptation and Use of Research Codes for Performance Assessment." PNL-SA-14592, Pacific Northwest Laboratory, Richland, Washington.

McMahon, L. A. 1984. 1985 Dodge Guide to Public Works and Heavy Construction Costs, ed. P. E. Pereira, 17th ed. McGraw-Hill Information Systems Company, Princeton, New Jersey.

Mills, M., and D. Vogt. 1983. A Summary of Computer Codes for Radiological Assessment. NUREG/CR-3209, U.S. Nuclear Regulatory Commission, Washington, D.C.

Mills, M., D. Vogt, and B. Mann. 1983. Parameters and Variables Appearing in Radiological Assessment Codes. NUREG/CR-3160, U.S. Nuclear Regulatory Commission, Washington, D.C.

Northiem, C. M., and R. S. Truesdale. 1986. Construction Quality Assurance for Hazardous Waste Land Disposal Facilities. EPA/530-SW-86-031, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

Richardson Engineering Services, Inc. 1983. Process Plant Construction Estimation Standards. Vol. 1, 1983-1984 ed., San Marcos, California.

Rogers and Associates. 1987. Conceptual Design Report: Alternative Concepts for Low-Level Radioactive Waste Disposal. DOE/LLW-60T, U.S. Department of Energy, Washington, D.C.

Rogers, V. C., and C. Y. Hung. 1987. Model Documentation PATHRAE-EPA Methodology and Users Manual. EPA 520/1-87-028, U.S. Environmental Protection Agency, Washington, D.C. Available on disk from C. Y. Hung, U. S. Environmental Protection Agency, Office of Radiation Programs, ANR 460, 401 M St. SW, Washington, D.C., 20460.

Science Applications International Corporation (SAIC). 1981. Tabulation of Waste Isolation Computer Models. ONWI-78, Oak Ridge, Tennessee.

Smith, C. F., and J. J. Cohen. 1980. "Models and Criteria for LLW Disposal Performance." In Proceedings of Modeling and Low Level Waste Management: An Interagency Workshop, Denver.

Tullis, J. A., and B. D. Reyes. 1988. "Low-Level Radioactive Waste Site Selection and Site Characterization Handbooks." In Proceedings of 10th Annual DOE Low-Level Waste Management Conference. CONF-880839-Ses. II, August 30-September 1, 1988, Denver.

U.S. Department of Energy (DOE). 1985. Computer Codes: A Bibliography. DOE/TIC-3386, Suppl. 1, Washington, D.C.

U.S. Department of Energy (DOE). 1988. "Radioactive Waste Management." DOE Order 5820.2A.

U.S. Environmental Protection Agency (EPA). 1986. Design, Construction and Evaluation of Clay Liners for Waste Management Facilities. EPA/530-SW-86-007, Draft Technical Resource Document for Public Comment (March 1986), Washington, D.C.

U.S. Environmental Protection Agency (EPA). 1988. Lining of Waste Containment and Other Impoundment Facilities. EPA/600/2-88/052, Cincinnati.

U.S. Nuclear Regulatory Commission (NRC). 1988a. Standard Format and Content of a License Application for a Low-Level Radioactive Waste Disposal Facility--Safety Analysis Report, Rev. 1. NUREG-1199, Washington, D.C.

U.S. Nuclear Regulatory Commission (NRC). 1988b. Standard Review Plan for the Review of a License Application for a Low-Level Radioactive Waste Disposal Facility--Safety Analysis Report, Rev. 1. NUREG-1200, Washington, D.C.

10 CFR 61. 1982. U.S. Nuclear Regulatory Commission, "Licensing Requirements for Land Disposal of Radioactive Waste." U.S. Code of Federal Regulations.

40 CFR 141. 1986. U.S. Environmental Protection Agency, "National Interim Primary Drinking Water Standards." U.S. Code of Federal Regulations.

APPENDIX A

DESCRIPTION OF SELECTED SORBENT MATERIALS

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The sorbent materials tested in this program are described below, along with the manufacturers' addresses.

ZEOLITES

Zeolites are a group of alumino-silicate minerals with a framework structure enclosing cavities occupied by large ions and water molecules. These large ions and water molecules have considerable freedom of movement, permitting ion exchange and reversible dehydration. Zeolites occur naturally in a number of locations around the world and are also produced synthetically. Common zeolites include clinoptilolite, phillipsite, chabazite, mordenite, and erionite. More information on zeolites can be found in Breck (1974); Mumpton (1976); Munson and Sheppard (1974); and Olson and Bisio (1984). Depending on the composition, zeolites can be very effective in sorbing a number of cations including Ca^{++} , Sr^{++} , Cs^+ , and Co^{++} , as well as a number of heavy metal ions. The manufactures of the zeolites tested in this program are given below:

Clinoptilolite

Teague Minerals
1925 Hwy 201 South
Adrian, OR 97901

Zeotech Corporation
P.O. Box 3400
Albuquerque, NM 87190

Synthetic Zeolites

Union Carbide
Linde Division
270 Park Ave
New York, NY 10017

CLAYS

Clay minerals such as bentonite and montmorillonite have ion exchange properties for cations such as Cs^+ . A discussion of clay minerals is provided in EPA (1986). The use of clays was not investigated in great detail as part of this program because the low permeability of clay would compromise the semi-porous nature of ESBs. The three clays that were tested in this program were bentonite, montmorillonite, and Indian red pottery clay. These materials tend to have a high affinity for cesium. The sources of these materials are:

Indian Red Pottery Clay

American Art Clay Company
4717 W 16th Street
Indianapolis, IN 46222

Bentonite Clay

Teague Minerals
1925 Hwy 201 South
Adrian, OR 97901

Montmorillonite

University of Missouri Curators
Source Clays
Dept. of Geology
University of Missouri
Columbia, MO 65211

GLAUCONITE

Glaucinite, also known as greensand, is a hydrous iron potassium silicate containing varying amounts of aluminum, magnesium, sodium, and trace elements. It was widely used as a fertilizer in New Jersey in the late 1700s (Markewicz and Lodding 1975). In the early 1900s it was found to have ion exchange properties that made it useful for water softening. Although it is known to be effective in removing calcium from water, its use in removing

strontium under the conditions used in this study was severely limited. Glaucinite did have a high affinity for cesium, however. The sample of glaucinite used in this study was obtained from:

Inversand Co.
P.O. Box 45
Clayton, NJ 08312

ACTIVATED CARBON

Activated carbon is widely used as an adsorption media for removal of organic and anionic species from aqueous solutions. Since activated carbon is most effective on anionic species, its purpose in the sorbent barrier is to removed organically complexed species such as EDTA-complexed cobalt. Activated carbon also has potential to remove other anionic species such as TcO_4^- . The source of the activated carbon used in this program was:

Calgon Carbon Corporation
P.O. Box 717
Pittsburgh, PA 15230-0717

REFERENCES

- Breck, D. W. 1974. "Ion Exchange Reactions in Zeolites." In Zeolite Molecular Sieves: Chemistry and Use, pp. 529-592. John Wiley and Sons, Inc.
- Markewicz, F. J., and W. Lodding. 1975. "Glaucinite." Industrial Minerals and Rocks 4:679-690.
- Mumpton, F. A. 1976. "Natural Zeolites: A New Industrial Mineral Commodity." In Natural Zeolites: Occurrence, Properties, Use, ed. L. B. Sand and F. A. Mumpton, pp. 3-26. Pergamon Press.
- Munson, R. A., and R. A. Sheppard. 1974. "Natural Zeolites: Their Properties, Occurrences, and Uses." Minerals Sci. Engng. 6(1):19-34.
- Olson, D., and A. Bisio, eds. 1984. Proceedings of the Sixth International Zeolite Conference, July 10-15, 1983, Reno, Nevada.
- U.S. Environmental Protection Agency (EPA). 1986. Design, Construction and Evaluation of Clay Liners for Waste Management Facilities. EPA/530-SW-86-007, Draft Technical Resource Document for Public Comment (March 1986), Washington, D.C.

APPENDIX B

PROCEDURES FOR MEASURING THE DISTRIBUTION COEFFICIENT (K_d) OF SORBENT MATERIALS AND SOILS

APPENDIX B

PROCEDURES FOR MEASURING THE DISTRIBUTION COEFFICIENT (K_d) OF SORBENT MATERIALS AND SOILS

BATCH CONTACT TEST

1. Dry the solids at 110°C for 24 h and allow to cool to room temperature. If the material will not be used immediately, seal it in an airtight container or bag.
2. Prepare a batch of solution containing ions of interest and adjust to the appropriate pH (expected pH in waste trench). The use of radioactive tracers is recommended because of the low detection limit and ease of simultaneous analysis of a number of radionuclides. If possible, an isotope that produces a strong gamma emission should be used. For instance, the use of ⁸⁵Sr in place of ⁹⁰Sr allows Sr to be analyzed simultaneously with radionuclides such as ⁶⁰Co and ¹³⁷Cs. Competing ions such as Na, Ca, Mg that may be present from waste form or soil must also be included.
3. Weigh 1 g of solid and place in a 250-mL polyethylene wide-mouth bottle.
4. Add 200 mL simulated leachate to the bottle and seal. Prepare at least one sample without any sorbent material for use as a blank. This will be a check in case a particular radionuclide tends to adsorb on the surface of the container.
5. Gently agitate bottles with a shaker platform or wrist shaker for a minimum of 72 h. Other time periods should also be investigated to determine if equilibrium conditions have been reached.
6. Filter or centrifuge solution to remove any solids. In most cases a 0.45 µm filter is sufficient to remove the solids. If very fine particle size material is used, a finer filter may be required.
7. Analyze a portion of the filtrate for all ions of interest. Analysis will also include a sample of the stock solution used in the experiments.

The solutions should be analyzed for the various radionuclides. Gamma or beta spectrometry should be used as appropriate for the analysis. Gamma spectroscopy generally requires less sample preparation than liquid scintillation counting, and a larger number of peaks can be resolved.

DATA ANALYSIS

A more convenient form of Equation (3.1) can be used to calculate the K_d for each radionuclide from the results of the radionuclide analyses.

$$K_d = \frac{(\text{vol liquid})}{(\text{weight solid})} \frac{(\text{Initial} - \text{Final})}{(\text{Final} - \text{Bkg})} \quad (\text{B.1})$$

where K_d = distribution coefficient, cm^3/g

vol liquid = volume of liquid in batch test, mL

weight solid = weight of the sorbent solid, g

initial = counts/ cm^3 for solution before contacting with solids
(stock solution)

final = counts/ cm^3 for solution after contacting with solids

bkg = background for counting system.

APPENDIX C

SAMPLE PATHRAE OUTPUT

APPENDIX C

SAMPLE PATHRAE OUTPUT

****Sample output from PATHRAE program when flag INPRINT is set to 1****

TOTAL EQUIVALENT UPTAKE FACTORS FOR PATHRAE

NUCLIDE	UT(J,1) RIVER L/YR	UT(J,2) WELL L/YR	UT(J,3) EROSION L/YR	UT(J,4) BATHTUB L/YR	UT(J,5) SPILLAGE L/YR	UT(J,6) FOOD KG/YR
Co-60	7.384E+02	4.816E+02	7.384E+02	7.384E+02	7.384E+02	5.397E-01
Sr-90	5.816E+02	4.816E+02	5.649E+02	5.762E+02	5.678E+02	1.173E+01
Cs-137	8.111E+02	4.816E+02	8.070E+02	8.111E+02	8.082E+02	2.746E+00

***** PATHRAE INPUT SUMMARY *****

THERE ARE 80 ISOTOPES IN THE DOSE FACTOR LIBRARY
 THE CUTOFF VALUE FOR NUCLIDE HALF LIVES IS 0.0 YEARS
 DEFAULT INVENTORY VALUE FOR CUTOFF NUCLIDES IS 0.00E-01 CI
 NUMBER OF TIMES FOR CALCULATION IS 10
 YEARS TO BE CALCULATED ARE ...

0.00	1.00	2.00	4.00	8.00
16.00	32.00	64.00	128.00	256.00

THERE ARE 3 ISOTOPES IN THE INVENTORY FILE
 THE VALUE OF IFLAG IS 0
 NUMBER OF PATHWAYS IS 1

PATHWAY	TYPE OF USAGE FOR UPTAKE FACTORS
2 GROUNDWATER TO WELL	3

TIME OF OPERATION OF WASTE FACILITY IN YEARS	20.
LENGTH OF REPOSITORY (METERS)	375.
WIDTH OF REPOSITORY (METERS)	375.
FLOW RATE OF RIVER (CUBIC METERS/YEAR)	3.57E+05
DISTANCE TO RIVER (METERS)	50.

DENSITY OF AQUIFER (KG/CUBIC METER)	1600.
LONGITUDINAL DISPERSIVITY (M)	0.00E-01
LATERAL DISPERSION COEFFICIENT -- Y AXIS (M**2/YR)	0.00E-01
NUMBER OF MESH POINTS FOR DISPERSION CALCULATION	20

FLAG FOR GAMMA PATHWAY OPTIONS	0
FLAG FOR ATMOSPHERIC PATHWAY	0
COVER THICKNESS OVER WASTE (METERS)	0.60
THICKNESS OF WASTE IN PITS (METERS)	4.90
TOTAL WASTE VOLUME (M**3)	6.000E-01
DISTANCE TO WELL -- X COORDINATE (METERS)	1.
DISTANCE TO WELL -- Y COORDINATE (METERS)	0.
DENSITY OF WASTE (KG/M**3)	1600.
FRACTION OF FOOD CONSUMED THAT IS GROWN ON SITE	0.220
FRACTION OF YEAR SPENT IN DIRECT RADIATION FIELD	0.228
DEPTH OF PLANT ROOT ZONE (METERS)	1.000
AREAL DENSITY OF PLANTS (KG/M**2)	0.000
AVERAGE DUST LOADING IN AIR (KG/M**3)	5.00E-07
ANNUAL ADULT BREATHING RATE (M**3/YR)	8035.
FRACTION OF YEAR EXPOSED TO DUST	0.228
CANISTER LIFETIME (YEARS)	0.
INVENTORY SCALING FACTOR	1.00E+00
HEIGHT OF ROOMS IN RECLAIMER HOUSE (CM)	240.
AIR CHANGE RATE IN RECLAIMER HOUSE (CHANGES/SEC)	5.56E-04
RADON EMANATING POWER OF THE WASTE	2.00E-01
DIFFUSION COEFF. OF RADON IN WASTE (CM**2/SEC)	2.00E-02
DIFFUSION COEFF. OF RN IN CONCRETE (CM**2/SEC)	6.00E-05
THICKNESS OF CONCRETE SLAB FLOOR (CM)	20.0
DIFFUSION COEFF. OF RADON IN COVER (CM**2/SEC)	1.14E-02
ATMOSPHERIC STABILITY CLASS	4
AVERAGE WIND SPEED (M/S)	2.01
FRACTION OF TIME WIND BLOWS TOWARD RECEPTOR	0.0930
RECEPTOR DISTANCE FOR ATMOSPHERIC PATHWAY (M)	345.0
DUST RESUSPENSION RATE FOR OFFSITE TRANSPORT (M**3/S)	2.51E-05
DEPOSITION VELOCITY (M/S)	0.0027
STACK HEIGHT (M)	1.0
STACK INSIDE DIAMETER (M)	0.00
STACK GAS VELOCITY (M/S)	0.0
HEAT EMISSION RATE FROM BURNING (CAL/S)	0.00E-01
FLAG FOR INPUT SUMMARY PRINTOUT	1
FLAG FOR DIRECTION OF TRENCH FILLING	1
FLAG FOR GROUNDWATER PATHWAY OPTIONS	1
AMOUNT OF WATER PERCOLATING THROUGH WASTE ANNUALLY (M)	0.400
DEGREE OF SOIL SATURATION	0.801
RESIDUAL SOIL SATURATION	0.000
PERMEABILITY OF VERTICAL ZONE (M/YR)	0.00
SOIL NUMBER	0.000

POROSITY OF AQUIFER	0.20
DISTANCE FROM AQUIFER TO WASTE (METERS)	0.0
AVERAGE VERTICAL GROUNDWATER VELOCITY (M/YR)	2.200
HORIZONTAL VELOCITY OF AQUIFER (METERS/YR)	35.000
MIXING THICKNESS OF AQUIFER (METERS)	10.000
SURFACE EROSION RATE (M/YR)	1.960E-04
ANNUAL RUNOFF OF PRECIPITATION (M)	3.22E-01

NUCLIDE NUMBER	NAME	INGESTION DOSE FACTORS (MREM/PCI)	INHALATION DOSE FACTORS (MREM/PCI)	DIRECT GAMMA DOSE FACTORS (MREM-M**2/PCI-HR)	VOLATILITY FACTOR (FRACTION)
44	Co-60	5.600E-06	4.000E-04	1.200E-08	2.500E-03
47	Sr-90	5.600E-06	2.000E-04	0.000E-01	2.500E-03
53	Cs-137	4.400E-05	5.000E-05	0.000E-01	2.500E-03

NUCLIDE NUMBER	NAME	EQUIVALENT UPTAKE FACTORS			GAMMA ENERGY (MEV)
		RIVER USAGE (L/YR)	WELL WATER USE (L/YR)	FOOD CONSUMPTION (KG/YR)	
44	Co-60	7.384E+02	4.816E+02	5.397E-01	1.250E+00
47	Sr-90	5.816E+02	4.816E+02	1.173E+01	3.390E-01
53	Cs-137	8.111E+02	4.816E+02	2.746E+00	6.620E-01

NUCLIDE NUMBER	NAME	INPUT LEACH CONSTANT(1/YR)	FINAL LEACH CONSTANT(1/YR)	GAMMA ATTENUATION(1/M)
44	Co-60	4.700E-03	4.700E-03	8.300E+00
47	Sr-90	5.900E-03	5.900E-03	2.000E+01
53	Cs-137	9.500E-05	9.500E-05	1.300E+01

NUCLIDE NUMBER	NAME	AQUIFER SORPTION	AQUIFER RETARDATION	VERTICAL SORPTION	VERTICAL RETARDATION
44	Co-60	0.000E-01	1.000E+00	1.000E+01	1.009E+02
47	Sr-90	0.000E-01	1.000E+00	8.000E+00	8.090E+01
53	Cs-137	0.000E-01	1.000E+00	5.000E+02	4.995E+03

NUCLIDE NUMBER	NAME	SOIL TO PLANT CONVERSION	HALF LIFE (YR)	INITIAL INVENTORY (CI)
44	Co-60	2.000E-02	5.250E+00	6.331E+04
47	Sr-90	2.500E+00	2.860E+01	3.170E+02
53	Cs-137	8.000E-02	3.000E+01	3.203E+02

PATHWAY 2
GROUNDWATER TO WELL

***** NUCLIDE DOSES FOR GIVEN TIMES *****

NUCLIDE	DOSE
44 Co-60	3.63E+03
47 Sr-90	6.70E+01
53 Cs-137	8.94E+00

***** SUM OF NUCLIDE DOSES FOR GIVEN TIMES *****
3 3.71E+03

***** SUM OF NUCLIDE RISKS FOR GIVEN TIMES *****
3 1.04E+00

***** DISPERSION CORRECTION FACTOR *****

NUCLIDE	VERTICAL FACTOR	HORIZONTAL FACTOR	TOTAL FACTOR
44 Co-60	1.00E+00	1.00E+00	1.00E+00
47 Sr-90	1.00E+00	1.00E+00	1.00E+00
53 Cs-137	1.00E+00	1.00E+00	1.00E+00

CONCENTRATION ARRAY CONCENTRATIONS IN CI/M**3

NUCLIDE	CONC	PEAK TIME
44 Co-60	1.35E-03	7.47E+00
47 Sr-90	2.48E-05	1.07E+01
53 Cs-137	4.22E-07	1.07E+01

APPENDIX D

HYDROLOGIC PERFORMANCE OF THE LOW-LEVEL WASTE TRENCH

APPENDIX D

HYDROLOGIC PERFORMANCE OF THE LOW-LEVEL WASTE TRENCH

Preliminary hydrologic analyses were conducted to determine the suitability of various trench designs with respect to drainage. The main objective of these preliminary analyses was to determine if the water that infiltrates the trench will drain sufficiently to prevent it from filling with water. The analyses were based on conservative simplifying assumptions. Drainage in one-dimensional systems was then numerically simulated to partially verify the conservativeness of the analytic analyses. The results of the modeling led to suggestions for improving both the trench design and the hydrologic performance analyses.

MATERIAL HYDROLOGIC PROPERTIES

The analysis of water movement in partially saturated porous materials generally requires that the hydrologic properties be known for all of the materials within the model region. These properties are 1) the volumetric liquid water content versus capillary pressure head relationship, and 2) the relative hydraulic conductivity versus capillary pressure head, or relative hydraulic conductivity versus water content, relationship. For the analyses discussed in this report, preliminary estimates of the material hydrologic properties were made based on 1) the trench design, 2) published data on soils from a humid region, 3) published data on similar materials from other locations, and 4) simplifying assumptions.

The model region was divided into four subregions (Figure D.1) for material property definition. Within each subregion, the material (soil, gravel, etc.) was assumed to be spatially uniform with respect to its hydrologic properties. The four subregions and their material types are 1) the soil used to backfill the trench following waste emplacement (fill soil; Soil A), 2) the gravel "pad" underlying the waste containers (gravel), 3) the engineered sorbent barrier (soil-zeolite mixture; ESB), and 4) the natural soil at the site (Soil B).

FIGURE D.1. Cross-Sectional View of SLB Trench Showing Dimensions Used in Equation (D.20)

Because only data on the upper 120 cm of Soil B (Gruber 1983) were available at the time of the analysis, Soil A and Soil B were assumed to be identical with respect to hydrologic properties. The volumetric liquid water content/capillary pressure head relationship of the soil was estimated using data presented in Figure 5 of Gruber (1983), as follows: first the water content/pressure head coordinates were digitized (data were not available in tabular form). Because of an equipment malfunction, the data points labeled "AVERAGE VALUES OBTAINED FROM FIELD CORES" in Gruber's Figure 5 were not digitized and thus were not used for estimation. Next, an analytic function was fit to the data using a computer program. The program uses a nonlinear least-square algorithm. The analytic expression proposed by Van Genuchten (1980) was assumed for the water content/pressure head relationship:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m}, \quad m = 1 - 1/n \quad (D.1)$$

where α and n are parameters to be determined, θ_r is the residual water content, θ_s is the water content at full saturation, θ denotes water contents, and h is suction head. Output from the computer program includes, among other information, estimates of the parameters θ_r , θ_s , α , n , and m (see Table D.1).

The hydraulic conductivity/water content relationship of the soil is assumed to be given by the following expression (Mualem 1976):

$$K = K_s S_e^L [f(S_e)/f(1)]^2 \quad (D.2)$$

where

$$f(S_e) = \int_0^{S_e} \frac{1}{h(S'_e)} dS'_e \quad (D.3)$$

L is a parameter (assumed to be 0.5), K_s is the hydraulic conductivity at full saturation, and S_e is the reduced water content: $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$. As in the water content/pressure head relationship, hysteresis is ignored. The saturated hydraulic conductivity, K_s , was estimated at 2.0×10^{-6} m/s based roughly on Figures 9 and 10 of Gruber (1983). Graphs of the fit characteristic curves for the soil are shown in Figures D.2 and D.3. The relative hydraulic conductivity is defined as the ratio of the hydraulic conductivity to the saturated hydraulic conductivity.

TABLE D.1. Parameters for Assumed Water Content/Pressure Head and Hydraulic Conductivity/Water Content Relationships

<u>Material</u>	<u>K_s, m/s</u>	<u>θ_s</u>	<u>θ_r</u>	<u>α, m^{-1}</u>	<u>n</u>	<u>m</u>
Soil	2.0×10^{-6}	0.41	0	1.75	6.05	0.835
Gravel	3.5×10^{-3}	--	--	--	--	--
ESB	--	0.53	0	0.172	1.19	0.163

FIGURE D.2. Experimentally Derived Water Content/Suction Head Data (x's), and Fitted Function, Soil

Results of laboratory tests on two samples of pure clinoptilolite were used to estimate the saturated water content of the sorbent barrier. Proctor tests were performed to determine bulk densities, which were then used to estimate the porosity, or maximum water content according to the following formula:

$$\theta_s = 1 - \frac{\rho_b}{\rho_s} \quad (D.4)$$

where ρ_b denotes bulk density and ρ_s denotes density of the grains. The grain density was assumed to be 2.6 g/cm^3 . The resulting estimates of θ_s are 0.47 for the <5 mesh sample and 0.53 for the -5+35 mesh sample. The 0.53 value was selected for use in the analyses reported below because this value corresponds to the finer of the two samples and thus seems more likely to be consistent with the assumed water content/pressure head and hydraulic conductivity/water content relationships (see below). The saturated

FIGURE D.3. Assumed Hydraulic Conductivity/Suction Head Relationship, Soil

hydraulic conductivity of the sorbent barrier was not estimated but, rather, was treated as an unknown to be determined according to design criteria.

The reduced water content/pressure head and relative hydraulic conductivity/water content relationships for the sorbent barrier were assumed to be identical to those estimated for a clay liner. The assumed relationships are of the same general functional form as those assumed for the soils (see above). The particular values of the relevant parameters are summarized in Table D.1. The assumed relationships are graphed in Figures D.4 and D.5.

The gravel used in the trench design was assumed to be a pea gravel, with an estimated saturated hydraulic conductivity of 3.5×10^{-3} m/s based on published data for similar gravels (Fayer et al. 1985; Freeze and Cherry

FIGURE D.4. Assumed Water Content/Suction Head Relationship, Sorbent Barrier

1979). For the preliminary analyses reported here, the flow of water through the gravel was not actually simulated; hence, it was not necessary to assign values for its other hydrologic properties.

ASSUMPTIONS

For the hydrologic analyses, the trench system was assumed to be in a steady state with respect to water flow. Also, if the sorbent barrier material is fine-grained relative to both the undisturbed soil below and beside the trench and the fill soil within the trench, it will tend to behave as a wick for soil moisture. Thus, if a zone of perched water forms in the trench, it will generally do so only after the sorbent barrier material becomes fully saturated. Therefore, we assumed that the sorbent barrier material is essentially fully saturated.

We assumed that all of the water that infiltrates the trench soil at the ground surface must exit the trench through one of two areas: the sloping trench walls or the horizontal trench bottom. If we ignore the possibility that some of this water may exit through the sloping trench walls, and

FIGURE D.5. Assumed Hydraulic Conductivity/Suction Head Relationship, Sorbent Barrier

instead assume that the sloping interface between the sorbent barrier and the undisturbed soil is impermeable, we will be conservative in the predictions. Since it would generally require two-dimensional simulations to determine exactly what proportion of the infiltrating water exits through the sloping walls, this simpler approach was chosen for preliminary analyses.

Mass conservation requires:

$$Q_{\text{TOP}} = Q_{\text{BOT}} \quad (\text{D.5})$$

where Q denotes volumetric flowrate. (The water is assumed incompressible.) The volumetric rate of flow into the trench (net infiltration) is:

$$Q_{TOP} = 2w_2 \cdot |q_{TOP}| \cdot L = 2w_2 \cdot q_{INF} \cdot L \quad (D.6)$$

where w_2 is the half-width of the upper surface of the trench, q_{INF} is the specific discharge due to infiltration, and L is the length of the trench. The volumetric rate of outflow through the trench bottom is:

$$Q_{BOT} = 2w_1 |q_{BOT}| \cdot L \quad (D.7)$$

where w_1 is the half-width of the horizontal trench bottom and q_{BOT} is the corresponding specific discharge.

We assume that the specific discharge at the trench bottom is downward and is the same all along this horizontal surface. Substituting the right-hand sides of Equations (D.6) and (D.7) for Q_{TOP} and Q_{BOT} in Equation (D.5), and simplifying, gives:

$$|q_{BOT}| = \frac{w_2}{w_1} \cdot q_{INF} \quad (D.8)$$

From the geometry of the trench design we know that:

$$w_2 = w_1 + \frac{L_1 + L_2 + L_3 + L_4}{M} \quad (D.9)$$

where L_1 = thickness of soil layer overlying waste containers
 L_2 = total thickness of waste region
 L_3 = thickness of gravel layer underlying waste containers
 L_4 = thickness of sorbent barrier lining trench bottom
 M = slope of trench wall, at interface between sorbent barrier and undisturbed soil.

Hence, the specific discharge through the trench bottom is:

$$|q_{BOT}| = \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{M w_1} \right] \cdot q_{INF} \quad (D.10)$$

Assume that the pressure head in the undisturbed soil at the bottom of the trench (at the sorbent barrier/soil interface) is zero or negative. This is expected to be the case because the undisturbed soil is coarser than the sorbent barrier material and hence can conduct an equivalent amount of liquid water while at a lower liquid saturation.

Under these conditions, the hydraulic gradient will be uniform throughout the sorbent barrier at the trench bottom. If the pressure head at the upper surface of the sorbent barrier, at the interface between the sorbent barrier and the gravel layer, is denoted by a , then the specific discharge through the sorbent barrier is (taking the pressure head to be zero at the barrier/soil interface):

$$|q_{BOT}| = K_{SB} \left[1 + \frac{a}{L_4} \right] \quad (D.11)$$

where K_{SB} is the hydraulic conductivity of the sorbent barrier at full saturation.

Neglecting capillary effects in the gravel and assuming that the hydraulic gradient within the gravel is uniform, the capillary pressure head at the interface between the sorbent barrier and the gravel layer, a , is related to the saturated thickness of the gravel, d , as follows:

$$a = \left[1 - \frac{|q_{BOT}|}{K_{GR}} \right] d \quad (D.12)$$

where $d \leq L_3$ and K_{GR} denotes the hydraulic conductivity of the gravel layer at full saturation. Substituting the right-hand side of Equation (D.12) for a in Equation (D.11), and solving for K_{SB} leads to:

$$K_{SB} = \frac{L_4 |q_{BOT}|}{L_4 + \left[1 - \frac{|q_{BOT}|}{K_{GR}} \right] d} \quad (D.13)$$

Then substituting the right-hand side of Equation (D.10) for $|q_{BOT}|$ in Equation (D.13) and rearranging leads to:

$$\frac{d}{L_4} = - \frac{1 - \frac{q_{INF}}{K_{SB}} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right]}{1 - \frac{q_{INF}}{K_{GR}} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right]} \quad (D.14)$$

Equation (D.14) summarizes the approximate steady hydrologic behavior of the lower portion of the trench in terms of dimensionless ratios.

APPLICATION

Equation (D.14) can be used in various ways. For instance, given set design parameters (d , K_{GR} , K_{SB} , L_1 , L_2 , L_3 , L_4 , M , and w_1) the following expression can be used to estimate the maximum steady infiltration rate that the design can accommodate:

$$q_{INF} = \frac{L_4 + d}{\left[\frac{L_4}{K_{SB}} + \frac{d}{K_{GR}} \right] \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right]} \quad (D.15)$$

This relationship was obtained by solving Equation (D.14) for q_{INF} . Alternatively, given an estimate of the infiltration rate, the following formula can be used to determine the minimum saturated hydraulic conductivity of the sorbent barrier:

$$K_{SB} = \frac{L_4 q_{INF} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right]}{L_4 + \left\{ 1 - \frac{q_{INF}}{K_{GR}} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right] \right\} d} \quad (D.16)$$

Equation (D.16) was derived by solving Equation (D.14) for K_{SB} .

Note that for the range of conditions considered here, the quantity in the denominator of the right-hand side of Equation (D.14) is very nearly equal to 1. Consequently, Equations (D.12), (D.14), (D.15), and (D.16) can be replaced with the following approximations, respectively:

$$a = d \quad (D.17)$$

$$\frac{d}{L_4} \approx \frac{q_{INF}}{K_{SB}} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right] - 1 \quad (D.18)$$

$$q_{INF} \approx \frac{K_{SB} (L_4 + d)}{L_4 \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right]} \quad (D.19)$$

$$K_{SB} \approx \frac{L_4 q_{INF}}{L_4 + d} \left[1 + \frac{L_1 + L_2 + L_3 + L_4}{Mw_1} \right] \quad (D.20)$$

These approximations implicitly assume that the saturated hydraulic conductivity of the gravel is high relative to the specific discharge, so that the fluid pressure distribution within the gravel is approximately hydrostatic. The specified value of d should always be less than or equal to L_3 , the total thickness of the gravel layer, so that the waste containers are neither wholly nor partially immersed in standing water indefinitely.

The actual infiltration rate, rather than staying constant in time, is expected to display some degree of temporal variability. Some of this variability may be, at least potentially, predictable (e.g., average seasonal variations, average diurnal variations). However, much of this variability is essentially stochastic and thus imparts uncertainty to water movement predictions. An additional source of uncertainty in the estimated infiltration rate is unknown measurement error. In principle, the analyses could be refined by directly incorporating transients and by taking a stochastic rather than deterministic approach, but such analyses would be much more involved and are beyond the scope of this report.

A simpler approach, used here, is to intentionally overdesign the waste facility, in an attempt to account for those uncertainties and shortcomings in the predictive model. This can be done, for example, by using inflated estimates of the infiltration rate, q_{INF} , and/or deflated estimates of the saturated thickness of the gravel, d , during the design stage. The difference between the total thickness of the gravel layer and the design saturated thickness then contributes to additional storage capacity for those periods that the actual infiltration rate may exceed the estimated average rate.

Example 1

Suppose that

$$L_1 = 1.22 \text{ m}$$

$$L_2 = 4.88 \text{ m}$$

$$L_3 = 1.52 \text{ m}$$

$$L_4 = 0.5 \text{ m}$$

$$M = 2/3$$

$$q_{INF} = 1.3 \times 10^{-8} \text{ m/s}$$

$$w_1 = 20 \text{ m}$$

Further suppose that to be somewhat conservative, we require that the saturated thickness of the gravel not exceed 0.25 m or about one-sixth of its

total thickness. Setting d equal to 0.25 m and substituting these values in Equation (D.20) gives the following lower bound for K_{SB} :

$$K_{SB} \geq 1.4 \times 10^{-8} \text{ m/s} \quad (\text{D.21})$$

For instance, we can estimate the maximum allowable steady infiltration rate corresponding to our current design using Equation (D.15). Setting

$$\begin{aligned} d &= 1.50 \text{ m} & L_3 &= 1.52 \text{ m} \\ K_{GR} &= 3.5 \times 10^{-3} \text{ m/s} & L_4 &= 0.50 \text{ m} \\ K_{SB} &= 1.4 \times 10^{-8} \text{ m/s} & M &= 2/3 \\ L_1 &= 1.22 \text{ m} & w_1 &= 20 \text{ m} \\ L_2 &= 4.88 \text{ m} \end{aligned}$$

in Equation (D.15) gives the upper bound

$$\max q_{INF} = 3.5 \times 10^{-8} \text{ m/s} \quad (\text{D.22})$$

which is about $(3.5/1.3 =)$ 2.7 times the current estimate of the average infiltration rate.

Example 2

This example is similar to Example 1 except that the values of q_{INF} and K_{SB} are changed. Suppose

$$\begin{aligned} d &= 0.25 \text{ m} & L_4 &= 0.50 \text{ m} \\ L_1 &= 1.22 \text{ m} & M &= 2/3 \\ L_2 &= 4.88 \text{ m} & q_{INF} &= 5.2 \times 10^{-8} \text{ m/s} \\ L_3 &= 1.52 \text{ m} & w_1 &= 20 \text{ m} \end{aligned}$$

Then Equation (20) gives the design value for K_{SB} :

$$K_{SB} = 5.6 \times 10^{-8} \text{ m/s} \quad (\text{D.23})$$

Setting d equal to 1.52 m and using $K_{SB} = 5.6 \times 10^{-8} \text{ m/s}$ in Equation (D.19) gives the theoretical maximum steady infiltration rate that the design can accommodate:

$$\max q_{INF} = 1.4 \times 10^{-7} \text{ m/s} \quad (\text{D.24})$$

which is approximately $(14/1.3 =)$ 11 times the current estimate of the infiltration rate.

Example 3

In this example, we investigate the effect of increasing the width of the sorbent barrier on the design saturated thickness and maximum infiltration rate. Let

$$\begin{aligned} K_{GR} &= 3.50 \times 10^{-3} \text{ m/s} & L_4 &= 2.00 \text{ m} \\ K_{SB} &= 1.4 \times 10^{-8} \text{ m/s} & M &= 2/3 \\ L_1 &= 1.22 \text{ m} & q_{INF} &= 1.3 \times 10^{-8} \text{ m/s} \\ L_2 &= 4.88 \text{ m} & w_1 &= 20 \text{ m} \\ L_3 &= 1.52 \text{ m} \end{aligned}$$

in Equation (D.18). Solving for d gives the design value:

$$d = 1.20 \text{ m} \quad (D.25)$$

which is less than L_3 , as it should be if the trench is to function properly. Using these same values in Equation (D.19), except resetting d to equal 1.52 m, gives the theoretical maximum allowable steady infiltration rate the design can accommodate:

$$\max q_{INF} = 1.4 \times 10^{-8} \text{ m/s} \quad (D.26)$$

which is approximately $(1.4/1.3 =)$ 1.1 times the current estimate of the infiltration rate.

ONE-DIMENSIONAL SIMULATIONS

Drainage was simulated in one-dimensional systems to partially corroborate the approximations derived earlier. Each simulation corresponds to one of the examples given previously. Inasmuch as these are one-dimensional simulations they can provide only a limited degree of verification. Given that 1) data on the material hydrologic properties are scarce, and 2) it is still relatively early in the design stage, it is impractical to perform more complex multidimensional simulations at this time.

In all of the simulations conducted, the system consisted of two layers: the sorbent barrier overlying and immediately adjacent to the undisturbed soil (Soil B). The upper boundary of the simulated system represented the gravel/ESB interface; the corresponding boundary condition was one of known specific discharge. The specific discharge was assumed to be uniform in time and was calculated according to Equation (D.10).

The lower boundary condition was one of known pressure head. The specified value was calculated as follows. If the lower boundary is sufficiently distant from the water table below it and the sorbent barrier above it, and the material at the boundary is sufficiently conductive, the steady-state hydraulic gradient is expected to be approximately negative 1. That is, the gravitational component of the hydraulic gradient is sufficient to drive the drainage at this point in the system. This is known as the unit gradient assumption. Under this condition, the hydraulic conductivity is equal to the magnitude of the specific discharge, which is known (see previous paragraph). So in effect, the hydraulic conductivity at the lower boundary is known. Using the hydraulic conductivity/pressure head relationship for the soil, the corresponding pressure head can be calculated.

For each simulation, an estimate of the steady-state pressure head distribution, consistent with these boundary conditions, was used as the initial condition. In all cases the initial pressure head distribution was such that the pressure head at the gravel/ESB interface was approximately equal to the design value of d , and the sorbent barrier was fully saturated. The soil was partially saturated.

All of the simulations reported here were performed using the UNSAT2 (Davis and Newman 1983) code, on a VAX 11/780 computer. UNSAT2 uses the finite-element method. In each case, the simulation was continued until the results indicated that the simulated system had approximately reached a steady state. This was determined to be true when the specific discharge at the lower boundary was very nearly equal to that at the upper boundary, and the pressure head at all nodes in the simulated domain experienced only negligible variations with time and these variations appeared to be decreasing in magnitude with time.

Simulation 1

This simulation corresponds to Example 1. The simulated system was one-dimensional, consisting of a 0.5-m-thick sorbent barrier overlying 1.88 m of undisturbed soil. The assumed values of some of the parameters are:

$$K_{SB} = 1.4 \times 10^{-8} \text{ m/s}$$

$$L_4 = 0.50 \text{ m}$$

$$L_1 = 1.22 \text{ m}$$

$$M = 2/3$$

$$L_2 = 4.88 \text{ m}$$

$$q_{INF} = 1.3 \times 10^{-8} \text{ m/s}$$

$$L_3 = 1.52 \text{ m}$$

$$w_1 = 20 \text{ m}$$

The specific discharge at the upper boundary was specified as $2.1 \times 10^{-8} \text{ m/s}$, and the pressure head at the lower boundary was specified as -0.7453 m .

One hundred and twenty days of drainage were simulated. At $t = 120$ days the lower part of the pressure head profile, corresponding to the soil, was very smooth with the pressure head changing less than $3 \times 10^{-5} \text{ m}$ over a distance of 0.4 m. Over much of the lower part of the profile the simulated pressure head was uniform with depth and equal to the value specified for the lower boundary. Similar behavior was observed in the lower simulations as well. This result suggests that the unit gradient assumption was valid for estimating the specified pressure head at the lower boundary.

The simulated pressure head at the upper boundary, which corresponds to the gravel/ESB interface, was equal to 0.23 m. This is slightly less than the 0.25 m value predicted by Equation (D.12), suggesting that the conceptual mathematical model is slightly conservative with respect to the prediction of drainage in one-dimensional systems. This difference does not appear to be significant.

Simulation 2

This simulation corresponds to Example 2 above. Here, all of the problem dimensions are identical to those of Simulation 1, but the assumed infiltration rate (q_{INF}) was increased to $5.2 \times 10^{-8} \text{ m/s}$. Also, the design value for K_{SB} was raised to $5.6 \times 10^{-8} \text{ m/s}$. For the simulation, the specific discharge at the upper boundary was specified at $8.4 \times 10^{-8} \text{ m/s}$. The pressure head at the lower boundary was specified at -0.6603 m .

In this case, 60 days of drainage were simulated. As in Simulation 1, the final value of the simulated pressure head at the gravel/ESB interface, d , was 0.23 m.

Simulation 3

This simulation corresponds to Example 3 above. Here, the simulated one-dimensional system consisted of a 2-m-thick sorbent barrier overlying 1.88 m of undisturbed soil. The parameters used in the simulation were assumed to have the following values:

$$K_{SB} = 1.4 \times 10^{-8} \text{ m/s}$$

$$L_4 = 2.00 \text{ m}$$

$$L_1 = 1.22 \text{ m}$$

$$M = 2/3$$

$$L_2 = 4.88 \text{ m}$$

$$q_{INF} = 1.3 \times 10^{-8} \text{ m/s}$$

$$L_3 = 1.52 \text{ m}$$

$$w_1 = 20 \text{ m}$$

The specific discharge at the upper boundary was specified as $2.1 \times 10^{-8} \text{ m/s}$, and the pressure head at the lower boundary was specified as -0.7453 m.

Sixty days of drainage were simulated in this case. At $t = 60$ days, the simulated one-dimensional system apparently had reached an approximately steady state. The simulated pressure head at the upper boundary was 0.97 m. Compare this number to the design value, $d = 1.20 \text{ m}$, given above in the discussion of Example 3. Again, the simulation results indicate that, at least as far as one-dimensional systems are concerned, our approximations tend to yield predictions that are conservative with respect to the drainage capacity of the sorbent barrier.

CONCLUSIONS

The simulation results presented earlier indicate that the assumptions embodied in Equation (D.11) result in conservative predictions of the drainage rate in one-dimensional systems. The approximate formulae (D.17), (D.18), (D.19), and (D.20) are intended to give conservative predictions of the drainage rate in the trench, but two-dimensional simulations and/or field experiments are required to fully verify this hypothesis. Therefore, it is recommended that the approximations developed here be used primarily during the early stages of the design process to guide the initial selection of desired hydrologic properties of the trench materials.

REFERENCES

- Davis, L. A., and S. P. Neuman. 1983. Documentation and User's Guide: UNSAT2--Variably Saturated Flow Model. NUREG/CR-3390, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Fayer, M. J., W. Conbere, R. R. Heller, and G. W. Gee. 1985. Model Assessment of Protective Barrier Designs. PNL-5604, Pacific Northwest Laboratory, Richland, Washington.
- Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey.
- Gruber, P. 1983. "A Hydrologic Study of the Unsaturated Zone Adjacent to a Radioactive Waste Disposal Site at the Savannah River Plant, Aiken, South Carolina." In Role of Unsaturated Zone in Radioactive and Hazardous Waste Disposal, eds. J. W. Mercer, P.S.C. Rao, and I. W. Marine, pp. 255-287.
- Mualem, Y. 1976. "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media." Water Resources Research 12(3):513-522.
- Van Genuchten, M. Th. 1980. "A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils." Soil Science Society of America Journal 44:892-898.

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