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TESTING AND MONITORING PLAN FOR THE PERMANENT ISOLATION SURFACE BARRIER PROTOTYPE

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MASTER

EXECUTIVE SUMMARY

This document is a testing and monitoring plan for a prototype barrier to be constructed at the Hanford Site in 1993. The prototype barrier is an aboveground structure engineered to demonstrate the basic features of an earthen cover system, designed to permanently isolate waste from the biosphere. These features include multiple layers of soil and rock materials and a low-permeability asphalt sublayer. The surface of the barrier consists of silt loam soil, vegetated with plants. The barrier sides are reinforced with rock or coarse earthen-fill to protect against wind and water erosion. The sublayers inhibit plant and animal intrusion and percolation of water. A series of tests will be conducted on the prototype over the next several years to evaluate barrier performance under extreme climatic conditions.

Prototype testing will include studies of water balance, wind and water erosion, and biointrusion. The prototype barrier will be sectioned into four major study plots, two of which will receive water at extreme application rates (either irrigation water or snow, depending on the season). Water balance testing will include detailed measurements of water content of surface soils using a combination of vertical and horizontal access ports for neutron probes. Continuous logging of time-domain reflectometry sensors will provide detailed water storage information on each of the four study plots. Drainage measurements will be made from pan-type drainage lysimeters installed under each study plot. There will be individual monitoring sections for soil and side slope areas on each plot, providing documentation of drainage from each area.

Thermal profiles will be obtained by data logging of strings of thermocouples. Other sensors, including thermal conductivity and heat dissipation sensors (calibrated for water content and water potential), will be installed at reference stations on each plot. The prototype will also be available for testing other non-intrusive sensors, such as ultrasound and ground-penetrating radar, for efficiency in documenting water movement in the soil profile.

Wind erosion testing will include characterizing the wind and saltating sand profiles over the barrier and evaluating erosion from the surface using erosion pins and surveying techniques. Water erosion will also be documented for each plot and the erosion potential of the steep side slopes carefully assessed, particularly after the water application tests. Biointrusion testing will be confined primarily to observation of root penetration into soil and sublayers using mini-rhizotron systems, which allow for root observations during and after plant establishment.

The effectiveness of an asphalt sublayer to shed water will be investigated. This layer, placed beneath the entire barrier, will be designed to perform as a low-permeability barrier, diverting the water that infiltrates the barrier on the sideslopes. This diverted water will be captured at the toe of the barrier slope and will be used by riparian vegetation growing there. It is intended that all water on the barrier will cycle back into the atmosphere via evapotranspiration. Assessment of how well this process works will be an important feature of the prototype testing and monitoring.

Design of the prototype was completed in June 1993. Construction is anticipated to begin in August 1993 and be completed in May 1994. Under this schedule, testing of the prototype will begin in May 1994 and will continue for a minimum of 3 years.

The design, construction, and testing of a prototype barrier is just one part, albeit an important one, of a larger program designed to address the technical issues associated with the performance of permanent isolation barrier systems. The utility of the prototype project is most readily understood by considering its role within the framework of the overall barrier development program.

ACKNOWLEDGMENTS

The development of permanent isolation barriers in general and the prototype barrier in particular is a joint effort being conducted by Westinghouse Hanford Company (WHC), Kaiser Engineers Hanford (KEH), and the Pacific Northwest Laboratory (PNL).

We appreciate the support and help of the Barrier Design Team from WHC, KEH, and PNL, whose initial input has stimulated the development of this testing and monitoring plan. Mr. Dick Wing, cognizant engineer for Protective Barrier Development activities at WHC, has been particularly helpful, providing comments and oversight throughout the development of this plan. Funding for the development of permanent isolation barriers and the prototype is provided by the U.S. Department of Energy's Office of Environmental Restoration and Waste Management under Contract DE-AC06-76RLO 1830.

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1.0 INTRODUCTION

The exhumation and treatment of wastes may not always be the preferred alternative in the remediation of a waste site. In-place disposal alternatives ultimately may be the most desirable alternative to use in the protection of human health and the environment. The implementation of an in-place disposal alternative will likely require some type of protective covering that will provide long-term isolation of the wastes from the accessible environment. (Even if the wastes are exhumed and treated, a long-term barrier may still be needed to adequately dispose of the wastes.) Currently, no "proven" long-term barrier system is available. The Hanford Site Permanent Isolation Surface Barrier Development Program (BDP) was organized to develop the technology needed to provide a long-term surface barrier capability for the Hanford Site. Initial work on barriers at the Hanford Site was begun in the early 1980s and focused primarily on constructibility of surface covers (Phillips et al. 1985). Since 1986, Westinghouse Hanford Company (WHC) has provided the overall engineering design and construction expertise for surface barriers, and the Pacific Northwest Laboratory (PNL) has provided technical support and expertise in testing of barrier performance. The current program, building on experience gained at Hanford and elsewhere, is designed to look at all aspects of long-term barrier performance.

The design of permanent isolation barriers is an evolving process. Each year, as new data and information are collected, valuable experience is acquired and insights into the approaches for solving barrier design problems are gained. During the development of a design for permanent isolation barriers, the need to construct and test full-scale prototypes of the latest barrier designs has become apparent. Such testing enables engineers and scientists to obtain field experience in constructing protective barriers and evaluating their performance. Construction issues that were not readily apparent on the engineering drawings may be more easily detectable in the field. Another valuable benefit of this approach is that the construction of prototype barriers forces all of the components of the barrier to be brought together into an integrated system. This integration is particularly important because some of the components of the protective barrier have been

developed independently of other barrier components. The integration also allows evaluation of the performance of the prototype barrier as a functional system.

Permanent isolation surface barrier systems are being developed to isolate wastes disposed of near the earth's surface at the Hanford Site. The permanent isolation surface barrier systems use engineered layers of natural materials to create an integrated structure with redundant protective features. Natural construction materials (e.g., fine soil, sand, gravel, riprap, asphalt) have been selected to optimize barrier performance and longevity. The objective of current designs is to use natural materials to develop a protective barrier system that isolates wastes for at least 1000 years by limiting water drainage; reducing the likelihood of plant, animal, and human intrusion; controlling the exhalation of noxious gases; and minimizing erosion-related problems.

Direction for the overall Hanford Site Permanent Isolation BDP is provided by the Barrier Development Plan. The Barrier Development Plan is the baseline planning document for the development of protective barrier systems on the Hanford Site. The plan identifies, describes, and relates logically the tasks required to resolve the technical concerns regarding protective barrier systems. The document is intended to provide information regarding technical developments, cost estimates, and scheduled completion dates of barrier and marker development tasks. The plan also provides general direction to and integration of all Hanford Site barrier studies. The prototype testing, as described here, is one part of the comprehensive plan for barriers at the Hanford Site. This plan was first written in 1986 (Adams and Wing 1986) and is currently under revision to reflect the present scope and direction of the barrier development efforts.

Thirteen groups of tasks identified in the Barrier Development Plan are intended to resolve technical concerns and complete the development and design of protective barrier systems. These task groups are listed below:

1. Biointrusion control
2. Water infiltration control
3. Erosion/deposition control

4. Physical stability testing
5. Human interference control
6. Procurement of barrier construction materials
7. Prototype barrier designs and testing
8. Natural barrier analog studies
9. Long-term climate change studies
10. Model applications and validation
11. Interface with regulatory agencies
12. Technology implementation and transfer
13. Final barrier design.

Figure 1.1 illustrates the organization of the 13 task groups that are input into the final design of the barrier and marker system. Specific test plans and other detailed documents have been or are being prepared to plan, schedule, execute, and report on each of the technology development activities within these task groups. The results of the tasks performed are documented and used 1) as input to other tasks whose activities are dependent on the results, 2) to improve computer simulation models, and 3) to develop detailed, final barrier and marker system designs. The appendix lists BDP documents published to date. Recent research activities related to barrier studies have been summarized by Cadwell et al. (1991).

This document focuses on the Prototype Barrier Designs and Testing task group. The design, construction, and testing of a prototype barrier at this stage of the BDP is an important activity. The current program began in 1986. Since then, the program's efforts have been focused on the development and testing of various barrier components that are based on preliminary barrier conceptual designs. For the most part, these development and testing efforts have been performed either in the laboratory or on relatively small-scale field plots. The issues being addressed pertain to protective barrier performance with respect to water infiltration, biointrusion, erosion and deposition, human interference, physical stability, and climate change. Studies of natural analogs of various barrier components are also being conducted. In addition, climate change studies are being used to predict future climatic conditions and to assess the performance of preliminary conceptual designs for barriers.

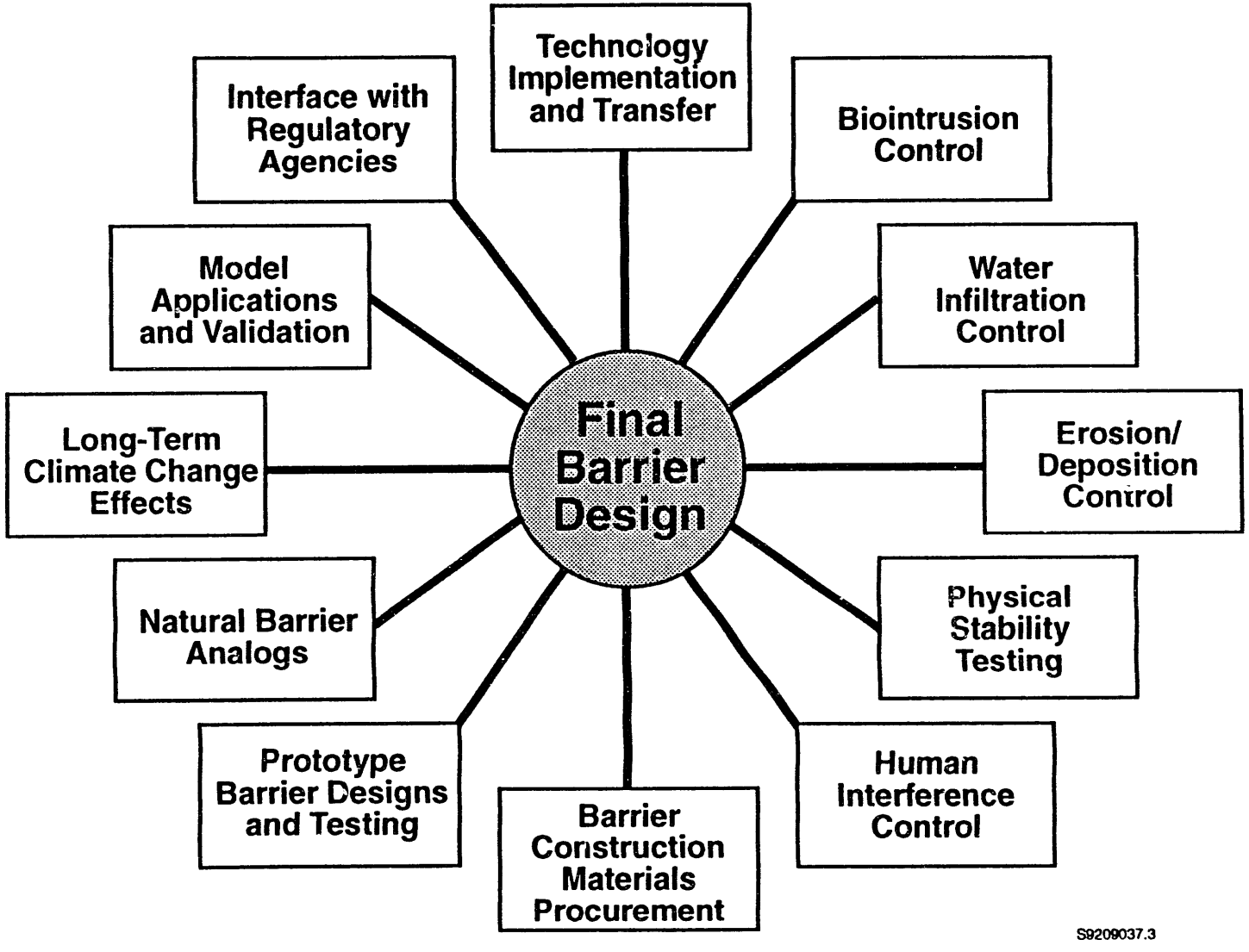

FIGURE 1.1. Development Tasks for Permanent Isolation Surface Barrier Program

The information and insights gained from these development tasks have enabled the BDP to progress to a point where the design and construction of a prototype is vital to continued barrier development. Although the results of development and testing efforts conducted so far are not final and additional work must be performed, enough information and data exist to allow the design and construction of a prototype. A full-scale prototype protective barrier will allow engineers and scientists to gain insights into and experience with issues regarding barrier design, construction, and performance that have not been possible with the individual tests and experiments conducted to date in the program.

This document provides a testing and monitoring plan for evaluating the performance of the prototype permanent isolation surface barrier.

2.0 SCOPE

The design, construction, and testing of a prototype barrier will require several years to complete. The design of the prototype was completed in June 1993. Construction of the prototype is scheduled to begin in FY 1994. Testing and monitoring of the prototype's performance will be required for at least 3 years following the construction of the prototype. Approximately 1 year is expected to be required for the prototype barrier to stabilize after construction is completed, instruments are installed, and experiments are initiated. Once the prototype stabilizes, a minimum of 2 years of testing and monitoring the performance of the prototype will be required. During that time, measurement of water infiltration, redistribution, and drainage from all components of the barrier, including the side slopes and subsurface asphalt layers, will provide quantification of barrier performance in terms of isolating waste from meteoric water sources, both under ambient and increased precipitation conditions. Effects of wind and water erosion as well as biointrusion will also be carefully documented. Details of the required testing and monitoring of the prototype are provided in the following sections. Continued monitoring of prototype barrier performance over extended periods of time is desirable but will be subject to the availability of funding as well as to the types of monitoring techniques used (i.e., destructive sampling). Additional performance data would provide increased confidence in long-term predictions of barrier stability and performance.

2.1 PROTOTYPE TESTING AND PERFORMANCE MONITORING

Once constructed, the prototype barrier will be tested and monitored to evaluate its performance over a range of conditions. A series of tests and experiments will be conducted on the prototype barrier to assess its performance with respect to water infiltration, biointrusion, erosion, and physical stability. Because there is only a relatively short time to test a prototype barrier that is intended to function for 1000 years or more, the testing program will be designed to "stress" the prototype so that barrier performance can be determined within a reasonable time frame.

Following prototype construction, it is expected to take about 1 year for the prototype to stabilize. During this year, the soil in the prototype barrier may experience a small but measurable amount of settlement. (Note that because of the location of the barrier over a stable crib, with an extremely stable coarse sand and gravel subbase, it is not expected that there will be significant differential settlement or subsidence). The actual amount of settlement will be fully documented. In addition, the moisture contents of the soils are expected to adjust from construction levels to more natural field conditions, and vegetation will become established on the barrier surface. Once the prototype barrier has stabilized, a baseline will exist from which test data on prototype performance can be collected. Performance data on water redistribution, drainage, erosion, stability, and intrusion by plants and animals should then be collected over a minimum of two complete growing cycles (fall and winter rainfall seasons and spring and summer growing seasons). Thus, a minimum of 3 years of rigorous monitoring and analysis of test data is required.

Other processes that will affect a protective barrier, including (but not limited to) succession of vegetation types, the full development of root profiles, and the natural colonization of the barrier surface by burrowing animals, occur over a longer period of time. Consequently, it is desirable to maintain a reduced level of monitoring beyond the 3-year period of rigorous monitoring. Funding will be sought to maintain the prototype as a long-term monitoring facility, because it should prove to be invaluable in hydrologic model validation studies and in the assessment of the long-term performance of cover systems at Hanford.

It should be noted that the construction of the prototype is, in itself, a test. Construction issues raised during the construction of the prototype will be analyzed and resolved in future barrier designs.

2.2 OBJECTIVES

There are several objectives for testing and monitoring the performance of a prototype barrier:

- Evaluate the effectiveness of various barrier components individually and as they interact to form a complete/whole engineered system.

- Provide large-scale testing of phenomena that are not adequately tested on small field plots, in laboratories, or with lysimeters.

- Determine parameters to be evaluated and the performance criteria to determine success and failure.

- Evaluate multiple, but limited, design alternatives for such factors as edge configuration and surface treatments.

- Identify instrumentation and measurement systems that enable quantifiable evaluation of barrier performance criteria (e.g., water infiltration through various layers).

- Provide a performance baseline by demonstrating barrier system functionality under stressed and ambient conditions. This involves planning methods to stress the barrier components by simulating extremes in environmental conditions and evaluating the desirability of stressing certain components to failure.

- Document the testing and monitoring activities for the purposes of peer evaluation and critique, regulatory review, and technology transfer.

- Obtain "buy-in" from regulators, end users, and technical peers regarding barrier performance.

- Provide a more accurate basis for estimating the costs associated with constructing permanent isolation barriers.

- Use the information and insights gained from testing activities to direct future barrier development activities.

These objectives provide general guidance for testing the prototype barrier. How these objectives in both general and specific ways will be met are described in subsequent sections of this report. It is anticipated that the success of the prototype tests, as measured by fulfillment of these objectives, will determine the ultimate successful use of surface barriers for waste isolation at the Hanford Site.

3.0 PRELIMINARY ACTIVITIES AFFECTING PROTOTYPE TESTING

Two "critical path" activities in the overall plan for the prototype barrier precede the actual testing and monitoring of the prototype. These two activities are 1) the siting of the prototype barrier, and 2) the construction of the prototype barrier. Appropriate siting considerations and construction timing are critical to the success of the prototype barrier's testing and monitoring program. The following two subsections discuss these activities.

3.1 SITING OF THE PROTOTYPE BARRIER

The prototype barrier, as currently designed, will be constructed on the 200 Area Plateau--at the 200-BP-1 Operable Unit. This operable unit (a designation for major cleanup areas at the Hanford Site) is located in the northwest quadrant of the 200 East Area. A detailed description of this site is provided in a report by Kaiser Engineers Hanford (KEH)(1993). The prototype barrier will be located over the B-57 Crib. A complete description of the siting of the barrier is given by KEH (1993).

The siting of the prototype at this location has several advantages and some disadvantages that should be recognized. A major advantage of the proposed site at the 200-BP-1 location is the connection of the prototype with an operable unit, and by association with this unit, an increased interest in the construction of the prototype by the regulatory community. A second advantage is the potential for an overall cost savings by using the prototype test as part of a "treatability test" for the operable unit. Locating the prototype over a crib provides a opportunity for study of surface isolation technology over an actual waste site. The prototype, built over an actual waste site, at field scale, will provide constructibility information that eventually may be transferable to larger construction activities for surface barriers on the Hanford Site. Authentication of barrier performance over an actual waste site is considered to be highly valuable information that may be needed to justify the planned construction of extensive surface barriers at Hanford. In this respect, the 200-BP-1 prototype is a critical test and should be regarded as a very high priority.

The prototype's location at 200-BP-1 (on the 200 Area Plateau) is suitable for obtaining accurate estimates of the costs associated with constructing protective barriers. Barrier construction costs are very sensitive to and comprise largely the costs associated with hauling construction materials. Most of the protective barriers that are being considered for waste site remediation activities at Hanford will be constructed on the 200 Area Plateau. Because the prototype barrier will be constructed at the 200-BP-1 location, representative and supportable costs for constructing barriers on the 200 Area Plateau can be estimated.

A distinct disadvantage of the placement of the prototype over the 200-BP-1 location is the inflexibility in modifications of testing and monitoring. Flexibility may be needed to ensure a final and satisfactory design. The 200-BP-1 location is a "hot" site and, as such, requires additional precautions in construction, testing, and monitoring. There are underlying wastes at the 200-BP-1 location; therefore, failure testing may be prohibited because of the associated risks. The use of the prototype as a test pad for innovative technologies in nondestructive testing and monitoring in the vadose zone also might be easier at a site that is more accessible for Hanford scientists and offsite subcontractors. Finally, it should be recognized that the costs for testing and monitoring at a "hot" site such as the 200-BP-1 location will be higher than at a "cold" site.

It should also be noted that the siting of the prototype barrier has been discussed with upper management in the environmental restoration (ER) and waste management (WM) programs at WHC. These discussions were necessary because many of the potential clients needing barrier technology are in the ER and WM programs (i.e., macroengineering, grout, single-shell tanks, solid waste burial, Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response, Compensation, and Liability Act remediation activities, and decontamination and decommissioning). The construction and testing of the prototype barrier, along with other barrier development tasks, will chart the course of barrier development activities throughout the remainder of the program. Consequently, having personnel in the ER and WM programs understand and concur with the proposed course of action at this early stage is essential.

3.2 CONSTRUCTION OF THE PROTOTYPE BARRIER

A comprehensive design for the prototype has been completed by KEH. An engineering report by KEH (1993) outlines the major features of the design and the schedule for completion of the barrier. The prototype is designed to represent a cover having two distinct side slopes (Figure 3.1). One side slope will be a relatively steep (2:1 horizontal to vertical) basalt rip-rap while the other side slope is "clean fill" material (consisting of local gravel/sand backfill) at a shallow (10:1) slope. The plan view of the prototype (Figure 3.1) shows an area of approximately 6000 m^2 for the four test sections. This area is underlain by a composite asphalt layer that is divided into a series of lysimeter pads leading to collectors that will be monitored over the course of the testing and monitoring period. Confirmation of the low permeability of the asphalt sublayer is made in two ways. First, a test pad of composite asphalt layer will be constructed coincident with the construction of the asphalt sublayer (but adjacent to the prototype). The pad will be tested for permeability and by inference the asphalt sublayer will be determined. Second, on a northeastern section of the test site, a geomembrane-type pan lysimeter will be constructed that will allow collection of all water that may seep through the asphalt sublayer. The pan lysimeter will be located under a section of the sublayer asphalt that is located under the coarse (basalt rock) side slope where maximum water infiltration is expected. Detailed design features of these sublayer structures, the diversion channels and the collection system for the entire barrier are provided by KEH (1993).

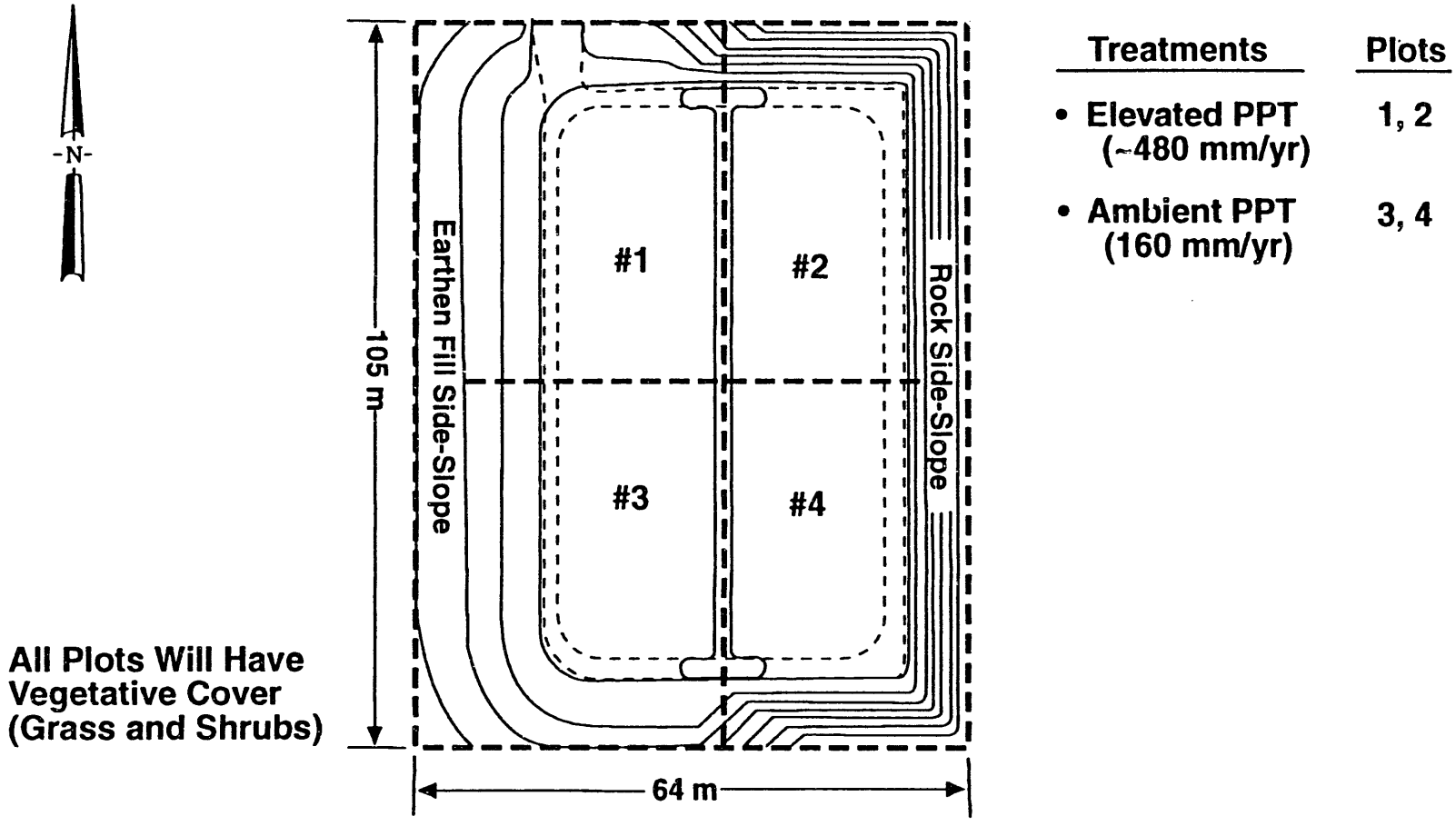

FIGURE 3.1. Plan View 200-BP-1 B-57 Cover System

4.0 PROTOTYPE BARRIER TESTING AND MONITORING ACTIVITIES

A number of tests and experiments will be conducted on the prototype barrier to assess the prototype's performance with regard to water infiltration, erosion, biointrusion, and physical stability. The following subsections provide detailed descriptions of 1) objectives of various types of tests that will be performed, 2) the techniques and equipment used, 3) the duration of the tests and experiments, 4) the expected results, and 5) any special considerations that needed to be input into the design of the prototype barrier. Information pertaining to the costs associated with the tests is contained in Section 5.0.

4.1 WATER INFILTRATION TESTS

A considerable amount of information about water balance (e.g., infiltration, drainage) is currently being obtained at the Hanford Site. At the Field Lysimeter Test Facility (FLTF) and the Small Tube Lysimeter Facility (STLF), studies are under way to quantify surface water balance both under conditions that are currently found at Hanford waste sites and under conditions that may exist when surface isolation barriers are emplaced (Gee et al. 1989, 1992; Campbell et al. 1990; Campbell and Gee 1990; Sackschewsky et al. 1991; Waugh et al. 1991). These lysimeter studies are perhaps the most extensive and precise water balance studies conducted at an arid site to date.

The Hanford Site lysimeter studies cited above show, for present climate conditions (i.e., 160 mm annual average precipitation) as well as for accelerated precipitation (up to 480 mm/yr), that surface barriers consisting of more than 1 m of fine soil over coarse subsurface materials are capable of preventing water from draining into underlying wastes. The lysimeter tests also demonstrate that without a surface barrier, underlying wastes could be subjected to leaching, because one-half or more of the annual precipitation has been shown to drain through coarse surface soils at Hanford (Gee et al. 1992).

Lysimeter studies, using containers ranging in size from 0.3 m diameter by 2 m deep to 2 m diameter by 3 m deep, are adequate for evaluating one-dimensional flow processes. Lysimeter studies have aided in initial selection

of cover materials and quantification of water balance (under present climate conditions) for a combination of selected soil-layer sequences. However, under increased precipitation, such testing becomes less useful, because flow is often two-and three-dimensional (e.g., runoff and subsurface lateral flow become more important). Studies that properly account for surface runoff and subsurface lateral flow are best carried out using larger-scale tests.

A prototype barrier, with subplots on the order of hundreds of square meters in size, will provide a facility in which field-scale processes of runoff and lateral flow can be studied in detail. The large-scale test areas will allow for direct comparisons of water infiltration into rock-covered side slopes and vegetated soil surfaces under different rates of water application (ambient and enhanced precipitation conditions).

The water infiltration tests will focus on surface water balance of relatively flat terrain (silt loam soil surfaces, vegetated with native grasses) and steep rock-covered side slopes. These tests will also be designed to quantify subsurface lateral-flow components. The introduction of an asphalt subsurface layer will be tested for water diversion to the side slopes and for redundancy in preventing drainage of water below multi-layered soil covers.

The prototype barrier is an ideal facility for testing the effectiveness of water infiltration control. Two major issues must be addressed in the prototype testing: 1) the effects that extreme precipitation events have on water infiltration, and 2) the effect of water infiltration on side slope stability and subsurface water content changes.

The first of these issues has been partially addressed with lysimeter tests at both the FLTF and STLF (Waugh et al. 1991; Gee et al. 1992). What has not been addressed in the earlier testing is the performance of a scaled-up barrier system. Can we expect the same response (of no water drainage) under elevated (up to 3 times) precipitation on large-scale barrier systems? Will the spatial variability of the barrier be controlled sufficiently (by careful construction) so that the barrier will perform in a manner similar to what we have seen with the lysimeter tests?

The second issue (side-slope infiltration) is one for which the prototype will provide unique and important data for final design of the protective barrier system. A key consideration in the final barrier design is how the side slopes will perform in protecting against erosion and internal water drainage.

4.1.1 Objective

The objective of the water infiltration task is to measure the complete water balance on the prototype barrier and, specifically, to identify the variations in water balance and drainage that occur on the soil-covered surfaces and compare these variations in drainage with those occurring on rock-covered side slopes. Furthermore, this task is designed to evaluate all factors that influence water balance of the prototype barrier under conditions that reflect both current and possible future climate conditions.

4.1.2 Technique(s)/Equipment

A series of techniques will be used for measuring and monitoring various components of the water balance. This includes measures of water application, drainage, water content, water potential, and temperature. Key measurements will be water application, collected by a series of recording and manual raingages; drainage, collected from subsurface drains; and soil water content, measured by both neutron probes and time-domain reflectometry (Wierenga et al. 1993). In addition, measurements of water potential will be made using thermal conductivity probes, and possibly resistance blocks, while temperature measurements will be made using thermocouples.

4.1.3 Water Application and Measurement

Water will be applied in several extreme-event scenarios using irrigation or snow. Figure 3.1 shows the planned treatments on the prototype barrier. Plots 1 and 2 will receive supplemental water, while plots 3 and 4 will receive ambient precipitation. Water will be applied using a specially designed irrigation system that can apply as much as 50 mm/h. A snow machine also may be used to test the prototype. A commercial, portable machine will be tested on an area adjacent to the barrier for performance and application of snow under Hanford Site conditions. If successful, it will be used for wintertime applications of precipitation. Rates representative of extreme

events, up to 68 mm in 1 day (28 mm in 1 h), will be applied in March of each year. If tests in FY 1993 prove feasible, snow cover applications of 1200 mm (with four applications, one each in November, December, January, and February) will be made using snow-making equipment in the winters of FY 1994, 1995, and 1996, to simulate extreme winter precipitations events.

Measurement of rain and irrigation water will be by standard raingaging. Measurement of snow will be in two ways. Snow depth will be recorded for each test plot by making a series of measurements at least weekly during snow season for naturally occurring snow events. Snow depth will also be measured for each test plot where artificial snow is applied (on irrigated plots). Snow will also be measured using specially constructed snow pillows or by use of heated raingages. In addition, there will be an effort to improve on standard raingaging for the prototype test. Mini-lysimeters, constructed of approximately 20-L containers, will be designed, built and tested to measure precipitation in the form of rain and snow. The mini-lysimeters will collect rain and snow in a removal bucket that is placed on a load cell. The load cell will measure weight changes over time and record precipitation events as they happen. Evaporation will be prevented by using a light oil film on the surface of the water and also by having a container cover that will readily collect water and snow at the container depth (at least 40 cm deep). Tests will be conducted before installation of the mini-lysimeters to ensure that they will not lose water to evaporation during the storm events. The increase in weight during snow or rain events will be treated as precipitation. Changes during periods of no snow will be discounted (i.e., weight loss caused by slow evaporation or weight gain from dust accumulation). It is also possible that the mini-lysimeters will be useful in some of the wind erosion testing that is planned for the prototype barrier.

4.1.4 Drainage Measurements from Soil Layers

A drainage system will be installed at depth under the soil surface. This will be a part of the prototype design, which includes an asphalt liner and collector pipes that allow separate measurements of drainage through the silt loam. A water metering system will be set up in an outflow tank (stilling well) with a drain-down-type "siphon sitter" that will allow measurement of drainage from a subsurface area of 300 m^2 or more with a precision of ±2 L

(equivalent to ±0.001 mm or less per recorded event). For low-flow situations, it will be necessary to prevent evaporation from the stilling well to ensure accuracy in drainage measurements. While negligible drainage is expected from the soil layer even under extreme events (e.g., winter snow melt, chinook winds, thunderstorms), the drainage collection system will be designed to collect water from the four major test areas (see Figure 3.1), both from side slopes and from soil layers located in these test areas.

4.1.5 Drainage Measurements from Side Slopes

A water collection system will be installed (asphalt barrier and collector pipes, etc.) under rock side slopes to measure drainage. A water metering system will be set up in an outflow tank (stilling well) to allow measurement of drainage from collector pipes. This will be an integral part of the prototype barrier and will collect drainage from an area of 400 m^2 or more to within a precision of ±2 L (equivalent to ±0.001 mm or less per recorded event). It is expected that there will be more than 5×10^5 L of water per year drained from each side-slope plot. Because it is important to ensure that water penetration through the asphalt layer is minimized, it will be important to document just how much water, if any, seeps through the asphalt layer placed under the rock side-slope, where maximum water infiltration is expected to occur. To accomplish this a specially constructed "pan lysimeter" will be located under a section of the rock side-slope. The pan lysimeter will be constructed of geomembrane material that is expected not to leak during the course of the experiment. Details of this collection system are provided by KEH (1993) in the protective barrier prototype engineering report. Because the "pan lysimeter" will be well below grade, it will be necessary to use a sump-type collection system to measure the drainage water. A tube for venting and a tube for vacuum extraction of the water will be installed and tested. Such a system will provide verification of drainage/or lack thereof from the asphalt pad. In addition to the pan lysimeter and its water removal system, a total of 12 drainage systems and collection units will be used to measure the drainage water from the test areas.

4.1.6 Water Diversion Observations

Water diversion from the non-test areas of the side slopes will be channelled to the toe of the slope. Beyond the toe of the slope there will be a relatively extensive area for water accumulation, where it is expected that riparian vegetation (shrubs and small trees) will become established over time. We will study the effects of the water diversion on the establishment of this vegetation. Neutron probe access ports will be installed in at least three key locations to document the water content changes that occur as a result of the water diversion and subsequent water uptake by the riparian vegetation. While this part of the barrier is not considered a critical component of the barrier, and the diversion of the drainage water can be accomplished in other ways (such as by underdrains and sumps), it is expected that vegetation may be a critical component to water removal and the drainage water should be available for vegetation. Such a system is not unlike the water-harvesting techniques that have been tried at the Hanford Site in the past (Sauer and Rickard 1982). Water harvesting relies on the concentration of water in wet periods of the year that can be available for crop production during periods of low rainfall. Sauer and Rickard (1982) showed that alfalfa and grapes could be grown on the Hanford Site, without irrigation, using water-harvesting techniques (where mounds of soil, covered with water repellent covers, diverted water into soil filled valleys between the mounds.

In the case of the prototype, there will be no attempt to produce commercial crops from "water harvesting" that will occur as water is diverted to the toe of the slope. Instead, native vegetation will use the water. The removal of water by vegetation, through transpiration processes, will be considered a positive factor in the isolation of wastes from water infiltration. A series of tests will be conducted at the toe of the slope using a selected set of plant communities that will be expected to be efficient in removing water from the soil during the course of the year. How much water will be supplied and how efficient the native plants will be in removing water from this zone will be the subject of tests of this component of the barrier water balance.

4.1.7 Soil Water Content Measurements

Horizontal access tubes will be installed in the prototype barrier to measure soil water with neutron probes. The access tubes will be placed in a layer sequence to measure the variation in water contents and water storage changes with time at the 1.8 m depth (in the silt loam soil, just above the silt loam-sand filter interface) and in the fill material underlying the asphalt layer at the base of the barrier. Vertical access tubes will also be used in selected locations in the upper 2-m of the barrier (in the silt loam soil) to profile the water storage conditions for each of four test plots.

At selected monitoring locations, surface water contents, to depths of 0.15 m, will be monitored using thermal conductivity probes that have been calibrated in terms of water content. This will allow for more precise measurement of water balance in the soil profile. In addition, as the testing proceeds there will be an effort to use the barrier prototype as a calibration site for non-invasive water content measurements. Such techniques as electromagnetic induction using commercially available geophysical logging equipment will be tested and compared to the neutron probe for profiling water content in the top 2 m of the barrier. We will also test commercially available capacitance probes for water content profiling. The capacitance probes are rapidly becoming an alternative to neutron probes for water content measurements in soils.

We will also test time-domain reflectometry (TDR) for water content profiling. TDR is a relatively new technique for measuring water content in soils, and it relies on the measurement of dielectric properties of materials that surround a buried cable or set of parallel rods. Because water has a dielectric constant of about 80 and soil minerals have dielectric constants of about 4, the measure of dielectric properties of a soil can be a reliable measure of its water content (Topp et al. 1980). The advantage of using TDR over neutron or capacitance probes is the ability to electronically log the water content on a nearly continuous basis. This allows for remote sensing of water content profiles and can reduce monitoring costs and virtually eliminate manual operation of probe equipment. Once the TDR probes (stainless-steel rods connected to coaxial cable) are placed in the ground they do not require retrieval nor calibration. There is no need to individually calibrate the

probes, provided the probes all have the same cable length and are properly connected to the electronic switching devices and the data logger. Because this is a relatively new technique some testing will be required to determine the optimum probe length and how well the soil and gravel admixture at the surface of the barrier and the silt loam below the surface conform to the standard calibration curve. Some of the testing required to evaluate the use of TDR for monitoring of the barrier can be accomplished at the FLTF. Part of the overall test plan will be to use the FLTF for such testing, because water content is known with great precision at the FLTF, and calibration of the probes over a range of water contents should be a relatively straightforward task. This can be accomplished during and after installation of the TDR equipment on the barrier. Timing for such testing will depend on the final cover placement. It is anticipated that there will be nearly one full year from the initiation of barrier construction before the TDR equipment is emplaced, because it will be one of the last things that will be done on the surface of the barrier (excavation for probe placement will be done rather than placement during construction).

4.1.8 Simple Tracer Test for Leakage

As an additional test, we also plan to evaluate the use of a borate tracer placed in the water to test for water content changes, particularly under the barrier. Geophysical testing equipment may be used that has a fast energy neutron generator that can detect low concentrations of borate-spiked water. If leaks occur in the asphalt, we anticipate that the fast neutron generator, coupled with capacitance probes, will be a useful diagnostic method for verifying water content changes. Water content changes under the asphalt can either be from leaks or simply the result of water accumulation under a low-permeable surface. The coupled measurement should identify the source of the water. (If borated water is detected under the asphalt, it can be assumed that leaks have occurred. If water content increases but no borate is found, it will be assumed that no leak has occurred.)

4.1.9 Temperature Measurements

Temperature sensors will be installed along the horizontal access tubes to monitor treatment effects on soil thermal regime. A total of about

50 temperature sensors (thermocouples) will be installed at four depths at four locations (at least one array of thermocouples in each of four plots). Thermal profiles will be used to document the effects of treatments on each plot and to identify potential contributions of non-isothermal effects on water movement in the cover throughout the year. The computer code, UNSAT-H (Fayer and Jones 1990) has the capacity to analyze for effects of temperature on water flow. Having thermal profiles will be valuable input into the complete analysis of water movement and water balance on the barrier.

4.1.10 Water Potential Measurements

Thermal conductivity (heat dissipation-type) sensors (that have been calibrated in terms of water potential or suction) will be installed at selected locations. These sensors will be installed at the base of the silt loam. A few (6 to 10) will be installed in at the base of the riprap layer. The purpose of these sensors are to document changes in the water potential at the soil/sand interface and to identify conditions when drainage is likely to occur. If water potential increases (suction decreases) to values approaching zero, there is a high probability that drainage will occur from the soil (silt) layer into the sand. The water potential measurements are expected to change little with time because the design will be sufficiently engineered that water contents will change little over time at depth. These measurements coupled with water content measurements will be treated as confirmatory measures of the direction of flow and the possible lack of drainage from the soil during the testing period.

4.1.11 Equipment Needs

The following equipment will be needed for water balance testing:

- 1 neutron probe with downwell and horizontal access capability (2 lengths of cable required)
- 1 capacitance probe--capable of being used in downwell and horizontal access holes
- 4 horizontal access tubes for neutron probe (emplaced during construction of the prototype)
- 20 vertical access tubes (2 m length) (emplaced during construction of the prototype).
- 50 thermal conductivity (heat dissipation) blocks for measurement of soil water potential
- 100 TDR probes and associated electronics for measuring water content
- 50 thermocouples for temperature measurement

14 stilling wells and "siphon sitters"
4 tipping bucket raingages
10 manual rain gages
4 small mini-lysimeters for measuring water content changes in soil profile (and can be used for precipitation-rain and snow)
1 irrigation system for wet treatments
1 snow-making machine for snow cover tests.

4.1.12 Duration

The equipment will be installed concurrent with and immediately after the construction of the prototype. The experiments are expected to begin in early FY 1994 and run through FY 1996. Although a 3-year testing period is currently planned, it is anticipated that the tests for water balance could continue through the next decade, as funding is made available. From our extensive studies at the FLTF and other test locations at the Hanford Site (Gee et al. 1992), we have determined that the longer the period of record that is available, the better the inferences of surface water balance can be. Three years is a minimum time period in which to draw any inference about water movement into and through a surface barrier.

The tests will provide key information on response of a surface barrier to extreme events and some inferences can be made about long-term water balance parameters. Such data on a large-scale field study are currently unavailable.

4.1.13 Expected Results

It is expected that the prototype tests for water balance will confirm the general conclusions from our earlier tests using lysimeters. The fine soil should act as a sponge and recycle and evaporate water even under extreme event situations. There should be no drainage from the soil cover when exposed to either ambient or elevated precipitation. However, we expect there will be a sizable amount of drainage from the rock side slopes. It will be important to test how well the asphalt sublayer performs in diverting water. We anticipate that the rock side slopes will contribute most, if not all, of the drainage. The system's capacity to handle subsurface flow and drainage will be quantified in our testing procedures. Such quantification is necessary for final barrier design considerations.

4.1.14 Design Considerations

It will be important to document the leakage rate from the asphalt sublayers that act as the primary drainage barrier. A pan-type lysimeter under the primary asphalt layer will be necessary for documenting the performance of the asphalt layer. Such a system is designed into the prototype. This double-layer system may not be needed in the final design of a permanent isolation barrier. However, the asphalt layers must be tested for permeability. Cores can be taken after initial placement and tested for durability, permeability, etc.

Some consideration will have to be given to handling large snowmelt events. Snow can be produced artificially by use of a snow-making machine. The effect of snow distribution, snow density, etc., will have to be evaluated. Quantities of water (in the form of snow) placed on the soil surfaces as well as side slopes will have to be carefully documented.

4.2 WATER EROSION MONITORING

The plan for monitoring the barrier's exposed soil cap proposes to collect data and information on the erosional behavior of the cap under natural rainfall and snowmelt conditions. The dominant erosional processes are those of rainsplash and overland runoff where rainsplash loosens soil particles and makes them available for transport by runoff. The prototype barrier will use both gravel admix and vegetation to reduce rainsplash erosion. A percentage by weight of gravel admix will be mixed with the soil during construction, and vegetation will be established after construction. The combined effects of rainsplash and runoff should be reduced by the process of gravel armoring and the interception of rainfall by a vegetation canopy.

Another factor contributing to runoff volume is the length of top surface slope, because a longer slope increases the cumulative effect of rainfall. The prototype provides the opportunity to monitor a representative length of barrier surface under local climatic conditions.

The plan for evaluating the gravel admix, vegetation, and slope length involves two separate data collection efforts: 1) the sampling and measurement of runoff and sediment yield from a 3-m-wide controlled strip (controlled

area monitoring) and 2) the observation and documentation of the effects of precipitation over the larger surface area outside of the controlled strip (barrier surface monitoring). Implementation of the monitoring system can be delayed until completion of construction. However, an evaluation of the location and placement of the controlled area should be done during construction.

As part of the barrier surface monitoring effort, the interface of the soil surface and rock riprap sideslope will be included in the observations. The rock sideslope will not be subject to erosion but erosional problems may develop at the interface caused by the loss of soil and filter material through the larger interstitial areas of the mounded rock. Such losses could lead to accelerated erosion of the barrier soil surface.

4.2.1 Barrier Surface Monitoring

4.2.1.1 Objective

The objective of this monitoring is to develop a baseline data base for the top surface soil/admix system with respect to erosion and soil surface "aging" under natural conditions. The data and information collected will be combined with results from an offsite test plot (located at the McGee Ranch) to identify design problems that develop over the life of the prototype, finalize top surface design criteria, and to provide supporting data and information to other tasks.

The data base will include measurements of the changes in engineering and soil properties at the surface, documentation of erosional patterns, the establishment of vegetation as it affects erosion, and disturbance by animals.

4.2.1.2 Technique(s)/Description

A permanent grid system will be established on the top surface on both sides of the center crown using standard engineering surveying methods. The grid will be designed based on data needs of both the wind and water erosion study tasks. Profile-level surveying methods will be used to collect elevation data at the grid points for analysis of consolidation and settlement. Engineering and soil properties will be collected monthly or seasonally to include wet and dry densities, percent compaction, and moisture content.

Surface soil changes, such as cracking and rill development, will be monitored with photography and located with respect to the grid system by engineering surveys.

Surveying equipment for layout of grid system and establish benchmarks is available at PNL. Surveying stakes, flagging, benchmarks,and other such material will be purchased. A Troxler gauge will be used to measure surface soil moisture and density and is available at PNL. Photographic records using 35-mm cameras will document surface changes. Aerial photography may be added but is not planned at this time.

4.2.1.3 Duration

The monitoring will be conducted on an as-needed basis, to be modified as needed (depending on observed erosion events). The grid system will be established immediately following construction and initial data taken at that time. The data collection will continue until immediately before any destructive sampling or investigations of the barrier. Four data collection events are scheduled for each year on a roughly seasonal basis.

4.2.1.4 Expected Results

Contour maps of the soil surface elevations and post-construction soil properties will be developed. Seasonal or annual changes in the elevations and properties will be documented using contour mapping over the life of the prototype barrier. Maps of changes in vegetation cover and animal burrowing will be developed to relate those changes to erosional trends. The mapping will document the degree of non-uniformity of near-surface moisture (localized accumulations) together with the other soil properties and any changes in those properties over the barrier life. Their relationship to erosion and infiltration will be investigated in cooperation with other tasks.

4.2.1.5 Design Considerations

No special considerations are required.

4.2.2 Controlled Area Monitoring

4.2.2.1 Objective

The objective of this testing is to quantify the amount of overland runoff from both rainfall and snowmelt and the associated sediment yields from the top surface as a function of time.

4.2.2.2 Technique(s)/Equipment

A 3-m-wide strip running the length of one side of the top surface from the crown to the side slope will be constructed in the 10-m-wide access area located in the center of the barrier. Runoff and sediment yield at the down gradient end of the strip will be collected in a system with a data logger. A separate grid system will be established for the controlled area. Changes in surface elevation will be documented using point-gage surveying, photography, or other field measurement techniques. Essentially the same data will be collected on the plot as on the barrier surface, but in more detail, and related to the water and sediment yield data measured over time.

A sediment collector will be installed at the downstream end of the flume to accumulate runoff and sediment. Flow meters will measure the inflow and outflow at the collector and a transducer will monitor the water levels in the collector system. This will provide cross-checking of the measured inflow and a record of low-volume runoff events. Soil moisture probes, thermocouple temperature indicators, and a snow gage will document snowmelt events. A rain gauge will be used as a backup system to validate rainfall at specific locations. A moisture sensor/relay turns the data logger on during storm events to reduce the amount of unwanted recorded information.

The following equipment will be used in this task:

2 automatic stormwater samplers w/flow meters
2 rain gages
4 thermocouple soil temperature probes
2 ambient air temperature probes
4 soil moisture probes
2 snow gages
2 leaf moisture sensors
2 fiberglass enclosures for equipment
2 6-V tape decks
1 tape reader card and software for PC
2 galvanized metal collection flumes

4 solar panels with appropriate power supplies for data logger/samplers
2 transducers
2 data loggers
1 electronic distance meter (EDM).

4.2.2.3 Duration

This test will last for the same period as that on the top surface area. The onsite servicing of the collector system will depend on the extent of precipitation and snowmelt events.

4.2.2.4 Expected Results

Time-varying measurements of overland runoff from rainfall and snowmelt events and corresponding sediment yield will be obtained. The data will be used to analyze erosion from precipitation falling on the barrier surface and the corresponding changes in erosivity as the surface ages. These results will provide information that will enable evaluation of the surface layer's capacity to resist water erosion.

4.2.2.5 Design Considerations

No special considerations are required.

4.3 WIND EROSION TESTS

Construction of a prototype barrier on the 200-BP-1 site will provide a usable location to obtain field information about eolian erosive stresses that will impact actual waste site barriers. This work is needed to compare full-scale field conditions with the results of physical models tested under controlled conditions in the wind tunnel (Ligotke 1993). Opportunities exist to 1) monitor the surface layer after construction and as it ages while exposed to natural conditions; 2) measure actual rates of surface deflation or inflation; 3) obtain micro-meteorological information about erosive shear stresses that impact the barrier, including the influence of the pile height and edge design on wind patterns; 4) obtain information about abrasive sand particle scouring (saltation); 5) create a sand dune and monitor its impact on surface erosion, plant community viability, and soil reservoir water balance; and 6) study erosive impacts after an artificial wildfire removes all surface vegetation. The first four eolian erosion monitoring tasks can be performed

immediately following construction and during the early years of the prototype study without impacting construction or other monitoring activities. Tasks 5 and 6 would be valuable for identifying the impacts of extreme climate and surface conditions. Task 5 should be performed during the period immediately following completion of other monitoring activities (perhaps 3 to 5 years after construction of the barrier). Task 6 may not be feasible given the location of the monitored barrier over and adjacent to an actual waste form, but would provide important information and should be considered.

4.3.1 Surface Layer Design, Placement, and Monitoring

4.3.1.1 Objective

This study will develop information that can be used to provide a surface layer that will protect the soil reservoir from eolian stresses. It will provide answers to questions such as: Are practical difficulties encountered during construction? Is it possible to maintain a uniform admixture composition?

4.3.1.2 Technique(s) and Equipment

The surface layer design will be based on water storage needs, animal intrusion, and water and wind erosion test results. A 15% (by weight) admixture of peagravel will be used in the top 1 m of the soil reservoir. It is important that all or most of the gravel pass a 3/8-in. sieve and be retained on a No. 10 sieve. "Protect from eolian stresses" is defined as the maximum acceptable deflation loss under worst-case conditions (perhaps 10 cm). Sieves will be used to test batches processed by the pug mill used to blend gravel with soil.

4.3.1.3 Duration

The period of the study will extend from pug mill operation through placement of the admixture to form the surface of the prototype barrier.

4.3.1.4 Expected Results

We anticipate the admixture will be placed according to the design and that its composition will stabilize the surface and protect it from eolian stresses. Quantification of the composition and the stability of the surface will be reported in monitored barrier status reports.

4.3.1.5 Design Considerations

The admixture batch composition must be verified during construction. Meeting the admixture design specifications constitutes a hold-point requirement in the construction process

4.3.2 Surface Deflation/Inflation Monitoring

4.3.2.1 Objective

This test will measure surface deflation or inflation rates and the initial and aging surface layer composition and morphology. The questions to be answered will reveal the impacts of erosion. Does the surface perform adequately under eolian stresses? If deflationary conditions prevail, are measured rates comparable to wind tunnel test results, does a gravel armor form, and do scoured areas form near upwind edges or in other areas? If inflationary conditions prevail, are sand deposits forming? What erosion is occurring on the side slopes? How does orientation and slope influence sideslope erosion?

4.3.2.2 Technique(s) and Equipment

The techniques used will follow the lead of the water erosion task to the extent that data needs are similar. The vertical distribution of gravel and sand in the surface layer will be measured. Immediately following construction, the task will document the uniformity of the admixture by sampling the surface layer at about 20 evenly or randomly spaced locations. Sampling devices and sieves will be used. For other types of equipment to be used in this activity, refer to the water erosion monitoring task (Section 4.2).

4.3.2.3 Duration

Surveys and sampling related to wind erosion monitoring should be performed once immediately after construction, and then approximately yearly throughout the life of the monitored barrier.

4.3.2.4 Expected Results

A comparison will be made between actual and design surface admixture gravel concentrations. Subsequent data are expected to show changes in the composition of the surface layer and changes in gravel and sand concentrations

that may impact the resistance of the surface to eolian erosion. These changes will be documented. It will be determined whether correlations exist between surface characteristics and deflation, inflation, and surface shear stresses (wind and sand saltation). We expect to find that the prototype surface performs as well as wind tunnel tests predict.

4.3.2.5 Design Considerations

Care will be required to ensure that the initial surface conditions for gravel admix meet the design specification. The applied admix should have a concentration of 15% (by weight) pea gravel. This should be considered a hold-point in construction.

4.3.3 Wind Stress Monitoring

4.3.3.1 Objective

This test will measure wind stresses on the approach, top edge, and top center of the prototype. The following questions will be addressed: Are peak values comparable, but less than, published values and those selected for wind tunnel tests? How much larger are wind stresses at the prototype top elevation than at ground level? Is the difference significant with respect to the ability of the barrier to resist deflation?

4.3.3.2 Technique(s) and Equipment

The vertical profile of wind will be measured using three masts having wind speed sensors at 0.25, 0.5, 1.0, and 2.0 m above the surface. Mean wind speed, peak gust intensity, and wind direction will be measured. Surface shear stresses will be calculated from boundary layer profiles. A single or multiple data loggers will also provide information needed for other studies by measuring temperature and soil moisture. The equipment to be used for this test includes 12 wind speed sensors and three wind direction, temperature, and soil moisture sensors, data acquisition system(s), masts, and supports.

4.3.3.3 Duration

Continuous sampling will be performed throughout the duration of the wind erosion monitoring effort.

4.3.3.4 Expected Results

Relative to their return period, peak wind shear stresses are expected to be comparable to those applied to physical models in a wind tunnel. The maximum stresses should range between roughly 2 and 4 N/m2. Stresses near the center of the barrier are expected to be greater than those at grade level and less than those near the edges. The relatively strong edge-region shear is expected to be greatest near the steep basalt sideslope and least near the graded sideslope. Although the surface layer should be able to resist wind stresses, the stresses present during the failure of any component of the barrier (surface layer, vegetation, sideslope, etc.) during any extreme wind events will be characterized.

4.3.3.5 Design Considerations

The optimum design and orientation of a monitored barrier, based on prevailing wind directions, is along a southeast-northwest or southwest-northeast axis. For a two-sideslope barrier, the steeper riprap sideslope would be placed on the southern and western perimeter. However, because the waste form in the 216-57-B crib is arrayed along a north-south axis, it is logical to construct the barrier in a similar orientation. Site topography also dictates that the steep riprap sideslope be located on the eastern half of the monitored barrier. Wind stress monitoring can be performed, however, regardless of this less than optimal orientation, by strategically positioning the top-edge sensor mast near the southeast corner. It is important that the access ramp not be located to the west or south of the top surface, its currently planned location to the northwest is acceptable. Mast installation will be performed after construction is complete.

4.3.4 Monitoring Saltation Stresses and Sand Drift Potentials

4.3.4.1 Objective

This test will measure saltation stresses and sand drift potentials near and on the monitored barrier. A series of questions will be addressed: Are peak values comparable to, but less than, the published values selected for wind tunnel tests? Are sand particle saltation stresses and sand drift potentials at the top surface of the monitored barrier greater or less than those

at ground level? Is the difference significant with respect to the capacity of the barrier to resist deflation?

4.3.4.2 Technique(s) and Equipment

Measurements will be made on the approach, to the top of the western graded sideslope, and on the monitored barrier surface between the center and the downwind edge. This arrangement will provide useful information for westerly winds from southwest to northwest. Two momentum profiling devices and/or four or six conventional saltating sand traps will be used.

4.3.4.3 Duration

Intermittent and seasonal measurements will be performed throughout the duration of wind erosion monitoring of the barrier.

4.3.4.4 Expected Results

Saltation stresses are anticipated to be greater on the surface of the monitored barrier than on the surrounding desert, because prevailing winds are likely to drive saltating sand along the graded sideslope and to the top of the barrier surface. (It is possible that some or much of this sand would be prevented from being transported to the barrier surface if a steep riprap sideslope were located on the western and southern perimeters; because of the planned orientation of the barrier, however, it is unlikely that this possible benefit can be investigated.) If present, saltating sand could provide the dominant erosive force on the surface of the barrier. Monitoring data will be used to quantify and evaluate the presence and influence of saltating sand grain shear stresses on the barrier surface. These stresses are expected to be equal to or less than the sand flux rates applied to physical models in a wind tunnel. Measured rates of sand transport will be correlated with meteorological and surface conditions and compared with published estimates.

4.3.4.5 Design Considerations

The planned graded sideslope on the western perimeter is the optimum design to provide a worst-case configuration for planned saltation monitoring on the surface of the monitored barrier. On the other hand, the use of only a steep basalt riprap sideslope might be the optimum choice to reduce sand

saltation impacts on above-grade barriers. This would of course, preclude the current objective of testing two sideslope configurations.

4.3.5 Monitoring an Artificial Sand Dune

4.3.5.1 Objective

Create an artificial sand dune on the surface of the barrier and monitor the resulting increase in saltation stress and sand drift potential. The questions to be answered impact surface erosion, vegetation, and water storage. Is a gravel armor formed and does it become stabilized? Does the sand dune migrate or cause a blowout to form? Is the stress sufficient to physically reduce or abrade plants? Do plants grow on the dune? Is the water balance in the underlying fine soil reservoir impacted?

4.3.5.2 Technique(s) and Equipment

This test will be performed after initial data cycles and any 1000-year flooding tests have been completed and the surface becomes dry. Clean dune sand having grain sizes predominantly between 50 and 500 μm will be placed on a portion of the surface on the west side so that a long fetch is presented to the northeast, east, and southeast. Sand drift and surface stress will be monitored as described in Section 4.3.4, and the same equipment will be used. After completion of the study the dune could be removed or enlarged and/or irrigated to provide a test of water balance in support of lysimeter data, if needed.

4.3.5.3 Duration

The test will last approximately 2 years, beginning about 3 to 5 years after construction of the monitored barrier.

4.3.5.4 Expected Results

It is expected that some sand from the dune will be blown off the barrier in saltation and some will be incorporated into the surface layer. Results of this activity will include a description of sand dune evolution on the top of the barrier and a characterization of saltating sand rates, stresses, and impacts on surface crusts and vegetation. If the dune dissipates with time, the ability of the surface to recover will be described.

4.3.5.5 Design Considerations

No special design considerations are needed.

4.3.6 Denudation of Vegetative Surface Cover

The monitoring activity is recommended because of its importance in addressing a near worst-case environmental condition that may periodically impact waste site barriers. It is recognized that one early challenge will be to identify a practical and acceptable method of removing vegetation from the surface, especially if the initial establishment of that vegetation is difficult. Removal of vegetation from the entire surface is preferred to removal from just a portion because it would allow continued testing of an irrigated condition and enhance the value of water balance and drainage studies.

4.3.6.1 Objective

In this test, the barrier will be stressed by burning or otherwise denuding the vegetative cover off all or part of the surface. Questions that will be addressed impact surface erosion, vegetation, and water storage. Is a gravel armor formed and does the surface stabilize? Is the water balance in the fine soil reservoir impacted? Is drainage measured from the asphalt layer? What type of vegetative cover becomes reestablished, and how long does it take? Should revegetation be influenced by seeding?

4.3.6.2 Technique(s) and Equipment

Initial work will require identifying a period for testing, determining which portion of the monitored barrier to test, and obtaining approval of the use of fire or another denudation technique. Monitoring of surface erosion, vegetative re-establishment, and water balance will use techniques and equipment developed and obtained in the completion of other monitoring activity tasks.

4.3.6.3 Duration

The test will last approximately 3 years, beginning about 3 to 7 years after construction of the monitored barrier. By using selected portions of the barrier, the test can be performed either in conjunction with the artificial sand dune test or after its completion.

4.3.6.4 Expected Results

Removal of vegetation by wildfire is expected to increase the impact of erosive forces. The evolution of the surface under wind and water stresses will be described. Rates of surface morphology change and surface deflation are expected to increase in the absence of vegetation and will be compared with those occurring when vegetation is present (using results of the annual surface surveys).

4.3.6.5 Design Considerations

No special design considerations are needed.

4.4 BIOINTRUSION TESTS

4.4.1 Vegetation Establishment and Monitoring

Vegetation will function as an important component of the protective barrier design. For the prototype barrier, a preferred vegetation cover must be determined and established as quickly as possible to ensure that other tests of water infiltration and surface erosion mimic expected barrier conditions as closely as possible. Successful vegetation establishment depends strongly on the careful reconstruction of the ecosystem.

4.4.1.1 Objective

Objectives of this subtask are to 1) determine a preferred vegetation cover for the prototype that will represent the vegetation expected to develop on fine soils under climate conditions on the 200 Area Plateau, 2) establish this fully functional vegetation cover as quickly as possible, and 3) monitor vegetative structure, dynamics, and water uptake characteristics. Issues that must be addressed to successfully establish this vegetation cover include topsoil deposition, fertilization, irrigation, appropriate microflora, seeding, and transplanting.

4.4.1.2 Technique(s)/Equipment

Instrumentation required to monitor and test the vegetation cover includes plant growth monitors and water relations monitoring devices (pressure bombs, porometers, and gas exchange equipment). Arrangements will have to be made to provide water at the prototype site for light irrigation.

4.4.1.3 Duration

Vegetation establishment will begin immediately after the construction of the prototype and continue during the following year. The prototype construction schedule calls for completion of the prototype barrier during FY 1993. Because of the seasonality associated with most effective plant establishment, it is important that all construction activities be completed on schedule so that vegetation establishment work can begin promptly in early fall of the year that the barrier is completed.

Monitoring of vegetation will be conducted annually after construction and should be continued throughout the testing period on the prototype barrier. Monitoring efforts are needed to determine the effectiveness of vegetation to recycle water out of the barrier surface and to aid in the development of hydraulic models.

4.4.1.4 Expected Results

A method of establishing vegetation will be identified (e.g., topsoil seed banks, seed, seedlings) that will enable rapid establishment of a plant community on the barrier surface. Success of the vegetation establishment task will be monitored by means of observations and measurements on the vegetation cover established on the prototype barrier. Standard quantitative measures of canopy cover will be used. The results will be used to support modeling and erosion evaluations of the prototype surface and will be compared with similar measures in comparable native vegetation stands and with measures of other vegetation establishment efforts on the Hanford Site.

Because other tasks depend on the establishment of the vegetation to acquire realistic data, the methods of establishing vegetation that will provide such cover in the shortest time frame will be given consideration first. The fastest means of establishment of a native community is to remove and store the top 30 cm of soil, which contains vegetation material, the seed bank, organics, and nutrients. This topsoil will be placed on the surface after the top 70 cm of fine soil has been deposited. Because we have not done a test of the effect of topsoil deposition on revegetation, we propose to test this technique before the prototype is built. If there is not enough time to complete this test, we will, in addition to topsoiling, place nutrients and

seeds and/or seedlings on the surface to increase the chances of a successful revegetation effort. The topsoil method will allow annual weeds to be represented; therefore, to better establish the deep-rooted perennials, the revegetated area will require watering into the summer season of at least the first year. However, while transplanting seedlings from native sources may seem a reasonable approach for establishing perennial cover on the prototype, it would not be reasonable from either a cost or labor standpoint for construction of full-size protective barriers.

4.4.1.5 Special Design Considerations

During construction of the prototype, three points are important to the establishment of vegetation: 1) the top meter of the fine-soil layer with 15% gravel admix may not exceed soil bulk densities of 1.6 g/cm^3, 2) nutrient amendments (yet to be determined) can be added to the top 15 cm of the fine-soil layer on the barrier (before to vegetation establishment), and 3) a source of water will be required for light irrigation during plant establishment.

4.4.2 Root Intrusion/Root Distribution

Vegetation will function as an important component of the protective barrier design, both to stabilize the soil surface and to extract soil moisture from the soil and recycle it to the atmosphere through evapotranspiration. For the prototype barrier design, in which fine soils overlie graded layers, we believe the optimal root distribution for barrier function will be one in which roots fully exploit the fine-soil layer. However, the establishment and growth of deep-rooted plants on the barrier present the possibility of intrusion of plant roots into the wastes and subsequent biotic transport of hazardous materials. Knowledge of root growth, root/soil interactions, and water uptake patterns is needed to model and predict the removal of soil water through evapotranspiration.

4.4.2.1 Objective

The main objectives of this subtask are to 1) evaluate the extent to which plant roots exploit the depth of the fine-soil layer under actual barrier construction conditions, and 2) determine whether the roots of established vegetation penetrate the various biointrusion control layers.

4.4.2.2 Technique(s)/Equipment

To monitor root distribution on the prototype barrier, a set of standard mini-rhizotrons will be placed in each moisture treatment to monitor plant root development and growth rates. These mini-rhizotrons will not penetrate past the fine-soil layer and will be augered into the fine-soil layer at a 45° angle after construction of the prototype is complete. A field-portable down-hole video camera will be required to record root distributions within the mini-rhizotrons.

To determine whether roots of established vegetation penetrate below the fine-soil layer, a layer of nonhazardous tracer (e.g., bromide) above the geotextile will be required.

4.4.2.3 Duration

Root distributions in the fine-soil layer will be monitored for at least 2 years after prototype construction. Depending on the success of plant establishment and rooting depths observed at that time, monitoring of root growth and development will continue as deemed necessary to document exploration of the fine-soil layer.

Most root intrusion testing will be conducted during FY 1994, 1995, and 1996. During FY 1995, data will be compiled, analyzed, and summarized in a final report on plant root distributions and intrusion in the barrier system.

4.4.2.4 Expected Results

Data from these endeavors will be used to construct a clear understanding of root distribution within the barrier under different moisture conditions and will be correlated with the aboveground vegetation structure. Analysis of leaf material sampled on an annual basis will determine whether tracer materials have been taken up by roots growing beyond the fine-soil layer. These data will be valuable in proving that anti-biointrusion layers prevent plant root intrusion into wastes, as well as providing information necessary for adequate model predictions of plant water uptake from barrier systems.

4.4.2.5 Design Considerations

During construction, the emplacement of a tracer layer above the high-density polyethylene (HDPE) layer will require a break in construction activities.

4.4.3 Animal Intrusion Subtask

The prototype barrier is not a convenient vehicle for testing the effectiveness of barrier components as deterrents to animal burrowing. (This should be done through independent testing where burrow stress can be maximized.) Nevertheless, evaluations of animal burrowing impacts on the prototype are desirable to parameterize the extent and nature of burrowing that occurs during the test life of the prototype.

4.4.3.1 Objectives

The objective of this testing is to document the extent of colonization of the barrier surface through the years when exposed naturally to burrowing animals of the Columbia Basin.

4.4.3.2 Techniques/Equipment

Periodic surveys of the barrier surface will be made to record the types and locations of natural burrowing. This activity will be initiated only after completion of the prototype but should continue for many years.

4.4.3.3 Instrumentation

Mapping of burrowing activity would be greatly facilitated by use of accurate, automated position-finding and recording instrumentation that keys to a reference location.

4.4.3.4 Duration

Measurements should be made quarterly at first, and then less frequently if the development of new burrows is found to be low. Measurements should continue to be made for the duration of the prototype testing and observation period, which is expected to be from 3 to 10 years.

4.4.3.5 Expected Results

Data collected will document burrowing animal invasion of the prototype barrier subsurface during the first several years after construction. Records of the animal species, numbers of burrows, the extent of burrowing disturbance, and the specific locations of burrows will aid in the overall evaluations of barrier performance. The records will aid in assessing results from other barrier performance measurements, such as water infiltration, should accelerated or enhanced infiltration occur in the vicinity of or as a result of animal burrowing.

4.5 ASPHALT TESTING

The majority of asphalt research performed at the Hanford Site has been for barriers used in the Uranium Mill Tailings and Hanford Grout Technology programs (Buelt 1983; Vallerga 1992). An asphalt composite system is being considered as an alternative to the RCRA bentonite clay/HDPE barriers as the low-permeability component in the HPB program. The asphalt composite barrier is composed of an asphalt-aggregate component overlayed with a polymer modified asphalt-geotextile membrane. Careful evaluation of the material properties (including long-term) and construction requirements for the composite asphalt barrier will be critical for constructing a successful prototype barrier.

There is an urgent need to develop a substitute for the standard RCRA clay/HDPE barrier cap system. RCRA barrier designs are only required to demonstrate a 30-year life cycle. These RCRA barriers may not be applicable for radioactive waste sites that require extremely long-term isolation or those located in arid sites where clay layers can become easily desiccated and susceptible to failure.

Clays are subject to desiccation cracking and root penetration and can be breached easily by animals and man. Clays also have finite hydraulic conductivities. The lowest conductivities expected in a typical RCRA-type clay cap are on the order of several centimeters per year. A clay-cap (based on current U.S. Environmental Protection Agency [EPA] design) that is subjected to prolonged wetting (such as would occur at humid sites, or under climate

changes that are likely to occur at arid and semi-arid sites in the future) would not be effective as a water isolation barrier. There is a high probability that in time, water transmitted through the clay will leach through the waste and carry contaminants to groundwater.

Asphalt/aggregate mixtures exhibit a range of permeabilities and physical stability characteristics (Hartley et al. 1981; Periasamy et al. 1990; Tuffour and Ishai 1990). The higher asphalt content is expected to improve the hydraulic conductivity and physical properties of the barrier. Liners with high asphalt contents also have been tested successfully and shown to minimize leachate losses from stored liquid wastes (Fitzgerald et al. 1970; MRM Partnership 1988; Terrel 1991). Asphalts have excellent binding, elongation, and shear stress properties when used in aggregate mixtures. Such mixtures are routinely used extensively in construction and their engineering properties are well documented for pavement construction applications. Equipment is readily available for large-scale testing and demonstration. Asphalts offer an attractive alternative to clay, provided the asphalt barrier system can be shown to be "RCRA equivalent" to clay barriers and the longevity of the asphalt system can be demonstrated through appropriate analysis.

Determining the RCRA equivalency and longevity of the asphalt composite barrier is crucial for obtaining "buy-in" from monitoring agencies such as the EPA and Washington State Department of Ecology for this new technology. Determining the RCRA equivalency of the asphalt composite barrier systems requires that:

- data be obtained from the prototype and test pad characterizing the in situ properties of the asphalt composite barrier and
- data be obtained in the laboratory characterizing the long-term physical properties of the proposed barrier.

Data obtained from the prototype and test pad will provide information on field performance, constructability and field conditions necessary for successful barrier installations. Long-term physical properties will be determined by conducting accelerated aging tests in the laboratory to establish a defensible design life criteria. In these tests barrier components will be exposed to gases at elevated temperature and pressure to simulate several hundred to several thousand years of exposure in the subsurface

environment. These conditioned materials will then be characterized for physical and permeability properties. Analog samples, in the form of asphalt artifacts (500 to 4000 years old), will be studied in the lab to provide insight into the physical properties of extremely aged asphalts (Heizer 1943; Forbes 1955; Gutman 1979). The measured properties of the aged materials will be used to perform structural analysis of the barrier systems to determine if they will remain effective under the anticipated site conditions.

4.5.1 Permeability Testing of Asphalt on the Prototype Barrier

4.5.1.1 Objective(s)

The objective of this testing is to determine the field performance of the asphalt-aggregate/asphalt-geotextile composite barrier. This information is crucial for determining if laboratory permeability and longevity behavior can be duplicated on a large-scale barrier placement. This information is critical to the determination of RCRA equivalency.

4.5.1.2 Technique(s)/Equipment

A test pad will be installed as part of the prototype barrier. This test pad is analogous to test pads required as part of RCRA compliance for clay/HDPE barriers. The test pad will be constructed of 15 cm of the asphalt-aggregate mixture with no asphalt-geotextile membrane. Construction of the test pad without the asphalt-geotextile component was selected to duplicate the requirements outlined by RCRA for testing the clay layer of RCRA barriers. A pan lysimeter will be installed under the test pad. The lysimeter will be configured so that a HDPE liner will be in direct contact with the bottom of the asphalt barrier. A double-ring infiltrometer will be installed on the test pad. The test pad will also be designed to "flood" the entire structure, if this approach is approach is deemed beneficial. The test pad will be designed so that intrusive testing, such as coring, can be performed without compromising the integrity of the lysimeter.

Asphalt content and aggregate gradation of the asphalt-aggregate mixture will be determined according to Washington State Department of Transportation (WSDOT) Quality Assurance/Quality Control (QA/QC) procedures. In situ air void content will be determined with Traxler-Nuclear Density gages, as

outlined in WSDOT specifications. Laboratory hydraulic conductivity measurements will be performed on cores retrieved for the test pad.

The prototype will be constructed by the same methods used on the test pad. Neutron probe access tubes will be included in the barrier design for monitoring moisture under the asphalt composite barrier. A double-ring infiltrometer will be installed in the 3X side slope area of the prototype. The 3X side slope area of the prototype represents an area where the potential for moisture intrusion is extremely high.

In situ permeability of the prototype will be monitored with permeameters that are an adaption of field permeameters used to measure the hydraulic conductivity of unsaturated-compacted soils as described by Fallow et al. (1993). These field results will be compared with laboratory hydraulic conductivity experiment results.

4.5.1.3 Duration

Monitoring should occur quarterly for the first few years to determine if there were any catastrophic failures attributable to construction techniques. After the first few years monitoring should occur twice a year. Additional monitoring should occur in the event of any extreme climatic or geologic events (100-year storm, earthquake, etc.). Monitoring should continue for the duration of the prototype testing and observation period (3 to 10 years).

4.5.1.4 Expected Results

If the asphalt composite barrier performs as expected, no measurable moisture over the saturated soil conditions should be detected. There is the possibility that moisture will condense under the asphalt layers as a result moisture intrusion from the sides of the barrier. This phenomenon will be evaluated as a possible interference to moisture measurements.

4.5.1.5 Design Considerations

QA/QC considerations during design and construction of the asphalt components of the barrier are critical. Materials and construction specifications derived from the pavement construction industry will likely make up the backbone of these specifications. These specifications will be evaluated to

determine their applicability to the barrier system. Extreme care will be taken to insure that the prototype barrier is installed as developed in the laboratory. This will be accomplished through the use of a stringent field QA/QC monitoring program.

5.0 COSTS OF TESTING AND MONITORING THE PROTOTYPE BARRIER

Testing and monitoring of the performance of the prototype barrier is a critical element of the BDP. The estimated costs of this effort are based on the most current personnel and overhead rates available.

The prototype project has been funded by both the Office of Technology Development (OTD) and the Environmental Restoration (ER) programs of DOE's Office of Environmental Restoration and Waste Management. Funding of the prototype construction is expected to be available from the ER program. It is anticipated that both OTD and ER will support the testing and monitoring cost for the prototype barrier over the next 4 years.

Table 5.1 provides a cost summary by task for the testing and monitoring of the prototype barrier.

TABLE 5.1. Cost Summary by Task (Thousands of Dollars)

Activity	FY 1993	FY 1994	FY 1995	FY 1996	FY 1997	Total
Water Infiltration						
Instruments and	407	0	0	0	0	407
Installation	0	495	475	475	450	1895
Testing/Monitoring	0	100	75	75	50	300
Side Slope-Evaporation						
Water Erosion						
Soil Surface Monitoring	0	48	66	69	73	256
Control Area Monitoring	0	93	59	62	65	279
Wind Erosion						
Surface Monitoring	10	20	0	0	0	30
Surface Deflation	0	30	20	20	25	95
Wind Stresses	20	85	60	60	75	300
Saltation	5	65	50	50	60	230
Sand Dune	0	0	0	5	50	55
Denudation	0	0	0	15	15	30
Biointrusion						
Root Intrusion	0	65	65	65	40	235
Vegetation Work	30	70	70	30	30	230
Animal Intrusion	0	20	30	30	20	100
Asphalt Testing						
RCRA Tests	80	400	30	30	30	570
Total	552	1491	1000	986	983	5012

6.0 QUALITY ASSURANCE

All testing and monitoring tasks supported by the prototype barrier project shall be performed in such a manner that the applicable QA program requirements are met. Throughout the testing and monitoring of the prototype barrier, various types of engineering and scientific information will be generated. This information will be analyzed, reviewed, and documented in status reports or other documents. The documentation will be cleared for public release (as applicable) and placed in archives according to approved QA procedures.

Data management for testing and monitoring of the prototype will be under PNL QA control. Data from water infiltration tests, including neutron probe data, water application, and water outflow data will be collected and input into laboratory record books (LRBs) and into data loggers and electronic data files. These files will be formatted for subsequent graphical display and analysis. Detailed records will be kept and LRBs will be reviewed as specified in the PNL-MA-70 QA Manual and as specified in the QA plan (OHE-002, Rev. 3) for the barriers program.

Data analysis will focus on quantifying barrier performance. Water balance of the test areas will be evaluated on an annual basis (or more frequently as necessary). Permeability of the composite asphalt layer (as discussed previously) will be analyzed immediately after testing and the data used to determine performance and design specifications. Acceptable limits of performance will be specified. In the case of the permeability, a 95% confidence interval, using standard statistical analysis, will be used to test against the hypothesis that the asphalt layer cannot meet the permeability limit of 0.5 mm/yr. If such a hypothesis is disproved (i.e., if the layer permeability is lower that 0.5 mm/yr) then the layer design will be determined to be acceptable. All other testing (water balance, water erosion, wind erosion) will be observational only. Limitation in design of the barrier does not allow for rigorous statistical testing of differences. Water balance test data will be used in model validation testing and verification.

7.0 REFERENCES

Adams, M. R., and N. R. Wing. 1986. *Protective Barrier and Warning Marker System Development Plan*. RHO-RE-OL-35P, Rockwell Hanford Operations, Richland, Washington.

Buelt, J. L. 1983. *Liner Evaluation for Uranium Mill Tailings: Final Report*. PNL-4842, Pacific Northwest Laboratory, Richland, Washington.

Cadwell, L. L. (ed.). 1991. *Hanford Site Protective Barrier Development Program: Fiscal Year 1990 Highlights*. PNL-7831, Pacific Northwest Laboratory, Richland, Washington.

Campbell, M. D., and G. W. Gee. 1990. *Field Lysimeter Test Facility: Protective Barrier Test Results (FY 1990, the third year)*. PNL-7558, Pacific Northwest Laboratory, Richland, Washington.

Campbell, M. D., G. W. Gee, M. J. Kanyid, and M. L. Rockhold. 1990. *Field Lysimeter Test Facility: Second Year (FY 1989) Test Results*. PNL-7209, Pacific Northwest Laboratory, Richland, Washington.

Fallow, D. J., D. E. Elrick, W. D. Reynolds, N. Baumgartner, and G. W. Parkin. 1993. "Field Measurement of Hydraulic Conductivity in Slowly Permeable Materials Using Early Time Infiltration Measurements in Unsaturated Media." In *Hydraulic Conductivity and Waste Containment Transport in Soils*. ASTM STP-1142, eds. D. E. Daniel and S. J. Trautwein. American Society for Testing and Materials, Philadelphia.

Fayer, M. J., and Jones, T. L. 1990. *UNSAT-H Version 2.0: Unsaturated Soil Water and Heat Flow Model*. PNL-6779, Pacific Northwest Laboratory, Richland, Washington.

Fitzgerald, C. T., H. W. Godbee, R. E. Blanco, and W. Davis. 1970. "The Feasibility of Incorporating Radioactive Wastes in Asphalt or Polyethylene." *Nucl. Appl. Technol.* Vol 9: December 1970.

Forbes, R. J. 1955. *Studies in Ancient Technology*, Vol. I, E. J. Brill, Leiden, Netherlands.

Gee, G. W., R. R. Kirkham, J. L. Downs, and M. D. Campbell. 1989. *The Field Lysimeter Test Facility (FLTF) at the Hanford Site: Installation and Initial Tests*. PNL-6810, Pacific Northwest Laboratory, Richland, Washington.

Gee, G. W., M. J. Fayer, M. L. Rockhold, and M. D. Campbell. 1992. "Variations in Recharge at the Hanford Site." *Northwest Sci.* 66:237-250.

Gutman, T. E. 1979. "The Use of Asphaltum Sourcing in Archaeology," *J. New World Archaeol.* 3:32-43.

Hartley, J. N. P. L. Koehmstedt, D. J. Esterl, H. D. Freeman, J. L. Buelt, D. A. Nelson, and M. R. Elmore. 1981. *Asphalt Emulsion Sealing of Uranium Mill Tailings 1980 Annual Report*. PNL-3752, Pacific Northwest Laboratory, Richland, Washington.

Heizer, R. F. 1943. "Aboriginal Use of Bitumen by California Indians." *Calif. Bur. Mines Bull.* 118:74.

KEH (Kaiser Engineers Hanford). 1993. *Engineering Report Prototype Surface Barrier at 200-BP-1 Operable Unit*. WHC-SD-EN-TI-142, Rev. 0, Westinghouse Hanford Company, Richland, Washington.

Ligotke, M. W. 1993. *Soil Erosion Rates Caused by Wind and Saltating Sand Stresses in a Wind Tunnel*. PNL-8498, Pacific Northwest Laboratory, Richland, Washington.

MRM Partnership. 1988. *Bituminous and Asphaltic Membranes for Radioactive Waste Repositories on Land*. Report to the Department of the Environment, DOE/RW/87.009, Bristol, England.

Periasamy, R, J. R. Newsome, A. L. Andrady, and D. S. Ensor. 1990. "Gas Permeability Measurements on Asphalts Using the Electrodynamic Balance." *Symposium on Chemistry and Characterization of Asphalts, Division of Petroleum Chemistry* 35:503-510, American Chemical Society, Washington, D.C.

Phillips, S. J., M. R. Adams, T. W. Gilbert, C. C. Meinhardt, R. M. Mitchell, and W. J. Waugh. 1985. *Engineered Barrier Test Facility Status Report: 1984*. RHO-WM-SR-3P, Rockwell Hanford Operations, Richland, Washington.

Sackschewsky, M. R., C. J. Kemp, L. L. Cadwell, M. E. Thiede, and W. J. Waugh. 1991. *Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990*. WHC-EP-0381, Westinghouse Hanford Company, Richland, Washington.

Sauer, R. H., and W. H. Rickard. 1982. *Restoration of Surface Mined Lands with Rainfall Harvesting*. PNL-4538, Pacific Northwest Laboratory, Richland, Washington.

Terrel, R. L. 1991. "Polymer Modified Hot-Mix Asphalt for Environmental Liners." *Hot Mix Asphalt Technol.* Spring 1991, pp. 14-17.

Topp, G. C., J. L. Davis, and A. P. Annan. 1980. "Electromagnetic Determination of Soil Water Content: Measurement in Coaxial Transmission Lines." *Water Resour. Res.* 16:574-582.

Tuffour, Y. A., and I. Ishai. 1990. "The Diffusion Model and Asphalt Age-Hardening." *Assoc. Asphalt Paving Technol.* 59:73-92.

Vallerga, B. A. 1992. *Characterization Study of Asphalt Concrete Barrier Materials for Radioactive Waste Vaults*. Status Report for Kaiser Engineers Hanford by B. A. Vallerga, Inc.

Waugh, W. J., M. E. Thiede, L. L. Cadwell, G. W. Gee, H. D. Freeman, M. R. Sackschewsky, and J. F. Relyea. 1991. "Small Lysimeters for Documenting Arid Site Water Balance." In *Proceedings of the International Symposium on Lysimetry*, ed. R. G. Allen, pp. 151-159. American Society of Civil Engineering, New York.

Wierenga, P. J., M. H. Young, G. W. Gee, R. G. Hills, C. T. Kincaid, T. J. Nicholson, and R. E. Cady. 1993. *Soil Characterization Methods for Unsaturated Low-Level Waste Sites*. NUREG/CR-5988, PNL-8480, prepared by Pacific Northwest Laboratory for the U.S. Nuclear Regulatory Commission, Washington, D.C.

Wing, N. R. 1992. *A Peer Review of the Hanford Site Permanent Isolation Surface Barrier Development Program*. WHC-MR-0392, Westinghouse Hanford Company, Richland, Washington.

Wing, N. R., and G. W. Gee. 1990. "Protective Barrier Development: Overview." In *Proceedings of the Twenty-Eighth Hanford Symposium on Health and the Environment, Environmental Monitoring, Restoration, and Assessment: What Have We Learned?* ed. R. H. Gray, pp. 147-151. Pacific Northwest Laboratory, Richland, Washington.

APPENDIX

PROTECTIVE BARRIER DOCUMENTS

APPENDIX

PUBLISHED PROTECTIVE BARRIER DOCUMENTS

1. Phillips, S. J., M. R. Adams, T. W. Gilbert, C. C. Meinhardt, R. M. Mitchell, and W. J. Waugh. 1985. *Engineered Barrier Test Facility Status Report: 1984*. RHO-WM-SR-3P, Rockwell Hanford Operations, Richland, Washington.

2. Phillips, S. J., T. W. Gilbert, and M. R. Adams. 1985. *Preliminary Engineering Specifications for a Test Demonstration Multilayer Protective Barrier Cover System*. RHO-WM-EV-8 P, Rockwell Hanford Operations, Richland, Washington.

3. Fayer, M. J., W. Conbere, P. R. Heller, and G. W. Gee. 1985. *Model Assessment of Protective Barrier Designs*. PNL-5604, Pacific Northwest Laboratory, Richland, Washington.

4. Myers, D. R. 1985. *Disposal Materials Study*. RHO-WP-EV-12P, Rockwell Hanford Operations, Richland, Washington.

5. Adams, M. R., and M. F. Kaplan. 1986. "Marker Development for Hanford Waste Site Disposal." In *Waste Management '86*, (Vol. 1), pp. 425-431, ed. R. G. Post. University of Arizona, College of Engineering and Mines, Tucson, Arizona.

6. Phillips, S. J., and J. N. Hartley. 1986. "Protective Barrier Systems for Final Disposal of Hanford Waste Sites." In *Waste Management '86*, (Vol. 1), pp. 433-437, ed. R. G. Post. University of Arizona, College of Engineering and Mines, Tucson, Arizona.

7. Kaplan, M. F., and M. R. Adams. 1986. "Using the Past to Protect the Future: Marking Nuclear Waste Disposal Sites." *Archeol.* 39(5):51-54.

8. Adams, M. R., and N. R. Wing. 1986. *Protective Barrier and Warning Marker System Development Plan*. RHO-RE-OL-35P, Rockwell Hanford Operations, Richland, Washington.

9. Fayer, M. J. 1987. *Model Assessment of Protective Barrier Designs: Part II*. PNL-6297, Pacific Northwest Laboratory, Richland, Washington.

10. Last, G. V., M. A. Glennon, M. A. Young, and G. W. Gee. 1987. *Protective Barrier Materials Analysis: Fine Soil Site Characterization*. PNL-6314, Pacific Northwest Laboratory, Richland, Washington.

11. Gee, G. W. 1987. "Preliminary Analysis of the Performance of the Protective Barrier and Marker System." In *Final Environmental Impact Statement, Disposal of Hanford Defense High-Level, Transuranic and Tank Wastes*, Appendix M, DOE/EIS-0113, U.S. Department of Energy - Richland, Operations Office, Richland, Washington.

12. Kirkham, R. R., G. W. Gee, and J. L. Downs. 1987. *Field Lysimeter Test Facility for Protective Barriers: Experimental Plan*. PNL-6351, Pacific Northwest Laboratory, Richland, Washington.

13. Waugh, W. J., and S. O. Link. 1988. *Barrier Erosion Control Test Plan: Gravel Mulch, Vegetation, and Soil Water Interactions*. WHC-EP-0067, Westinghouse Hanford Company, Richland, Washington.

14. Wing, N. R., M. D. Campbell, J. L. Downs, G. W. Gee, R. R. Kirkham, and S. J. Phillips. 1988. "Protective Barrier Development: The Field Lysimeter Test Facility." In *Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management Spectrum '88*, pp. 196-198. American Nuclear Society, Inc., La Grange Park, Illinois.

15. Phillips, S. J., M. S. Ruben, and R. R. Kirkham. 1988. "Engineered Surface Barriers for Waste Disposal Sites: Lysimeter Facility Design and Construction." In *DOE Model Conference Proceedings*, pp. 1229-1238. CONF-881054. Oct. 3-7, Martin Marietta, Oak Ridge, Tennessee.

16. Ligotke, M. W. 1988. *Soil Erosion Rates from Mixed Soil and Gravel Surfaces in a Wind Tunnel: A Preliminary Report*. PNL-6677, Pacific Northwest Laboratory, Richland, Washington.

17. Waugh, W. J., and M. G. Foley. 1988. *Protective Barrier Climate-Change Impacts: Technical Workshop Findings and Recommendations*. PNL-6615, Pacific Northwest Laboratory, Richland, Washington.

18. Ligotke, M. W. 1989. *Surface Stability Test Plan for Protective Barriers*. PNL-6722, Pacific Northwest Laboratory, Richland, Washington.

19. Gee, G. W., R. R. Kirkham, J. L. Downs, and M. D. Campbell. 1989. *The Field Lysimeter Test Facility (FLTF) at the Hanford Site: Installation and Initial Tests*. PNL-6810, Pacific Northwest Laboratory, Richland, Washington.

20. Gee, G. W., M. D. Campbell, H. D. Freeman, and J. F. Cline. 1989. *Assessment of Cover Systems at the Grand Junction, Colorado Uranium Mill Tailings Pile: 1987 Field Measurements*. PNL-6762, Pacific Northwest Laboratory, Richland, Washington.

21. Petersen, K. L. 1989. *The Long-Term Climate Change Assessment Task of the Hanford Site, Washington Protective Barrier Development Program*. WHC-SA-0537-FP, Westinghouse Hanford Company, Richland, Washington.

22. Cadwell, L. L., L. E. Eberhardt, and M. A. Simmons. 1989. *Animal Intrusion Studies for Protective Barriers: Status Report for FY 1988*. PNL-6869, Pacific Northwest Laboratory, Richland, Washington.

23. Freeman, H. D., G. W. Gee, and J. F. Relyea. 1989. *Field Study Plan for Alternate Barriers*. PNL-6840, Pacific Northwest Laboratory, Richland, Washington.

24. Freeman, H. D., and G. W. Gee. 1989. *Hanford Protective Barriers Program Asphalt Barrier Studies - FY 1988*. PNL-6874, Pacific Northwest Laboratory, Richland, Washington.

25. Waugh, W. J. 1989. *Gravel Admix, Vegetation and Soil Water Interactions in Protective Barriers: Experimental Design, Construction and Initial Conditions*. PNL-6616, Pacific Northwest Laboratory, Richland, Washington.

26. Freeman, H. D., and G. W. Gee. 1989. *Hanford Protective Barriers Program: Status of Asphalt Barrier Study - FY 1989*. PNL-7513, Pacific Northwest Laboratory, Richland, Washington.

27. Link, S. O., and W. J. Waugh. 1989. *Evapotranspiration Studies for Protective Barriers: Experimental Plans*. PNL-6899, Pacific Northwest Laboratory, Richland, Washington.

28. Petersen, K. L. 1990. "The Long-Term Climate Change Assessment Task of the Protective Barrier Development Program for Low-Level Waste Site Remediation at the Hanford Site, Washington." In *High Level Radioactive Waste Management*. Vol 2, pp. 1235-1239. Proceedings of an International Topical Meeting. American Nuclear Society, La Grange, Park, Illinois. (WHC-SA-0808-FP, Westinghouse Hanford Company, Richland, Washington).

29. Fayer, M. J. 1990. *Test Plan for Hydrologic Modeling of Protective Barriers*. PNL-7152, Pacific Northwest Laboratory, Richland, Washington.

30. Wing, N. R., and G. W. Gee (eds). 1990. *Hanford Site Protective Barrier Development Program: Fiscal Year 1989 Highlights*. WHC-EP-0318, Westinghouse Hanford Company, Richland, Washington.

31. Campbell, M. D., G. W. Gee, M. J. Kanyid, and M. L. Rockhold. 1990. *Field Lysimeter Test Facility: Second Year (FY 1989) Test Results*. PNL-7209, Pacific Northwest Laboratory, Richland, Washington.

32. Landeen, D. S., L. L. Cadwell, L. E. Eberhardt, R. E. Fitzner, and M. A. Simmons. 1990. *Animal Intrusion Field Test Plan*. WHC-EP-0253, Westinghouse Hanford Company, Richland, Washington.

33. Link, S. O., M. E. Thiede, R. D. Evans, J. L. Downs, and W. J. Waugh. 1990. *Evapotranspiration Studies for Protective Barriers: FY 1988 Status Report*. PNL-6985, Pacific Northwest Laboratory, Richland, Washington.

34. Relyea, J. F., M. R. Sackschewsky, and W. J. Waugh. 1989. *Small-Tube Lysimeter Facility Status Report for Fiscal Year 1989*. WHC-EP-0297, Westinghouse Hanford Company, Richland, Washington.

35. Walters, W. H., K. A. Hoover, and L. L. Cadwell. 1990. *Project Test Plan for Runoff and Erosion on Fine-Soil Barrier Surfaces and Rock-Covered Side Slopes*. PNL-6791, Pacific Northwest Laboratory, Richland, Washington.

36. Hoover, K. A., L. L. Cadwell, and W. H. Walters. 1990. *Hanford Protective Barriers Program: Water Erosion Studies - FY 1989*. PNL-7214, Pacific Northwest Laboratory, Richland, Washington.

37. Landeen, D. S. 1990. *Animal Intrusion Status Report for Fiscal Year 1989*. WHC-EP-0299, Westinghouse Hanford Company, Richland, Washington.

38. Ligotke, M. W., and D. C. Klopfer. 1990. *Soil Erosion Rates from Mixed Soil and Gravel Surfaces in a Wind Tunnel*. PNL-7435, Pacific Northwest Laboratory, Richland, Washington.

39. Waugh, W. J., M. E. Thiede, C. J. Kemp, L. L. Cadwell, and S. O. Link. 1990. *Field Study of Gravel Admix, Vegetation, and Soil Water Interactions: Protective Barrier Program Status Report - FY 1989*. PNL-7440, Pacific Northwest Laboratory, Richland, Washington.

40. Hunter, C. R., A. J. Busacca, and W. J. Waugh. 1990. *A Feasibility Study of Modeling Pedogenic Carbonates in Soils and Sediments at the U.S. Department of Energy's Hanford Site*. PNL-7413, Pacific Northwest Laboratory, Richland, Washington.

41. Wing, N. R., and G. W. Gee. 1990. "Protective Barrier Development: Overview". In *Proceedings of the Twenty-Eighth Hanford Symposium on Health and the Environment, Environmental Monitoring, Restoration, and Assessment: What Have We Learned?* ed. R. H. Gray, pp. 147-151. Pacific Northwest Laboratory, Richland, Washington.

42. Wing, N. R., and G. W. Gee. 1990. "Protective Barrier Development: Overview". In *Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management Spectrum '90*, pp. 335-337. American Nuclear Society, Inc., La Grange Park, Illinois.

43. Glantz, C. S., M. N. Schwartz, K. W. Burk, R. B. Kaspar, M. W. Ligotke, and D. J. Perrault. 1990. *Climatological Summary of Wind and Temperature Data for the Hanford Meteorology Monitoring Network*. PNL-7471, Pacific Northwest Laboratory, Richland, Washington.

44. Campbell, M. D., and G. W. Gee. 1990. *Field Lysimeter Test Facility: Protective Barrier Test Results (FY 1990, The Third Year)*. PNL-7558, Pacific Northwest Laboratory, Richland, Washington.

45. Sackshewsky, M. R., J. C. Chatters, S. O. Link, and C. A. Brandt. 1991. *Protective Barrier Program: Test Plan for Plant Community Dynamics.* WHC-EP-0380, Westinghouse Hanford Company, Richland, Washington.

46. Nichols, W. E. 1991. *Comparative Simulations of a Two-Layer Landfill Barrier Using the Help Version 2.0 and UNSAT-H Version 2.0 Computer Codes.* PNL-7583, Pacific Northwest Laboratory, Richland, Washington.

47. Landeen, D. S. 1991. *Animal Intrusion Status Report for Fiscal Year 1990.* WHC-EP-0398. Westinghouse Hanford Company, Richland, Washington.

48. Campbell, M. D., G. W. Gee, R. R. Kirkham, S. J. Phillips, and N. R. Wing. 1991. "Water Balance Lysimetry at a Nuclear Waste Site." In *Proceedings of the International Symposium on Lysimetry*, ed. R. G. Allen, pp. 125-134. American Soc. Civil Engr., New York.

49. Kirkham, R. R., M. L. Rockhold, G. W. Gee, M. J. Fayer, M. D. Campbell, and L. J. Fritschen. 1991. "Lysimeters: Data acquisition and analysis." In *Proceedings of the International Symposium on Lysimetry*, ed. R. G. Allen, pp. 362-370. American Soc. Civil Engr., New York.

50. Phillips, S. J., J. F. Relyea, C. J. Kemp, N. R. Wing, M, D, Campbell, G. W. Gee, M. J. Graham, R. R. Kirkham, and M. S. Rubin. 1991. "Development of Hanford Site Lysimeter Facilities." In *Proceedings of the International Symposium on Lysimetry*, pp. 19-27, ed. R. G. Allen. American Soc. Civil Engr., New York.

51. Waugh, W. J., M. E. Thiede, L. L. Cadwell, G. W. Gee, H. D. Freeman, M. R. Sackschewsky, and J. F. Relyea. 1991. Small Lysimeters for Documenting Arid Site Water Balance. In *Proceedings of the International Symposium on Lysimetry*, pp. 151-159, ed. R. G. Allen. American Soc. Civil Engr., New York.

52. Cadwell, L. L. (ed.) 1991. *Hanford Site Protective Barrier Development Program: Fiscal Year 1990 Highlights.* PNL-7831, Pacific Northwest Laboratory, Richland, Washington.

53. Petersen, K. L. 1991. *Modern and Pleistocene Climatic Patterns in the West.* WHC-EP-0523, Westinghouse Hanford Company, Richland, Washington.

54. Chatters, J. C., and H. A. Gard, 1991. *Archaeological Mounds as Analogs of Engineered Covers for Waste Disposal Sites Literature Review and Progress Report.* PNL-7718, Pacific Northwest Laboratory, Richland, Washington.

55. Sackschewsky, M. R., C. J. Kemp, L. L. Cadwell, M. E. Thiede, and W. J. Waugh. 1991. *Status Report for the Small-Tube Lysimeter Facility Fiscal Year 1990.* WHC-EP-0381, Westinghouse Hanford Company, Richland, Washington.

56. Fayer, M. J., M. L. Rockhold, and D. J. Holford. 1992. *Model Assessment of Protective Barriers: Part III Status of FY 1990 Work.* PNL-7975, Pacific Northwest Laboratory, Richland, Washington.

57. Petersen, K. L. 1992. *A Warm and Wet Little Climate Optimum and a Cold and Dry Little Ice Age in the Southern Rocky Mountains, U.S.A.* WHC-SA-1382-FP, Westinghouse Hanford Company, Richland, Washington.

58. Link, S. O., M. E. Thiede, J. L. Downs, D. J. Lettau, and W. J. Waugh. 1992. *Evapotranspiration Studies for Protective Barriers: FY 1989 Status Report.* PNL-8033, Pacific Northwest Laboratory, Richland, Washington.

59. Link, S. O., J. L. Downs, M. E. Thiede, D. J. Lettau, T. R. Twaddell, and R. A. Black. 1992. *Evapotranspiration Studies for Protective Barriers: FY 1990 Status Report.* PNL-8032, Pacific Northwest Laboratory, Richland, Washington.

60. Fayer, M. J., M. L. Rockhold, and M. D. Campbell. 1992. "Hydrologic Modeling of Protective Barriers: Comparison of Field Data and Simulation Results." *Soil Sci. Soc. Am. J.* 56:690-700.

61. Wing, N. R. 1992. *A Peer Review of the Hanford Site Permanent Isolation Surface Barrier Development Program.* WHC-MR-0392, Westinghouse Hanford Company, Richland, Washington.

62. Gee, G. W., M. J. Fayer, M. L. Rockhold, and M. D. Campbell. 1992. "Variations in Recharge at the Hanford Site." *Northwest Sci.* 66:237-250.

63. Ligotke, M. W. 1993. *Soil Erosion Rates Caused by Wind and Saltating Sand Stresses in a Wind Tunnel.* PNL-8478, Pacific Northwest Laboratory, Richland, Washington.

64. Fayer, M. J. 1993. *Model Assessment of Protective Barriers: Part IV, Status of FY 1992 Work.* PNL-8498, Pacific Northwest Laboratory, Richland, Washington.

65. Wing, N. R., and G. W. Gee. 1993. *The Development of Permanent Isolation Surface Barriers: Hanford Site, Richland, Washington, U.S.A.* WHC-SA-1799-FP, Westinghouse Hanford Company, Richland, Washington.

66. Petersen, K. L., J. C. Chatters, and W. J. Waugh. 1993. *Long-Term Climate Change Assessment Study Plan for the Hanford Site Permanent Isolation Barrier Development Program.* WHC-EP-0569 Rev. 1, Westinghouse Hanford Company, Richland, Washington.

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