SGW-44980
Revision 0

Technical Basis for Evaluating Surface Barriers to Protect Groundwater from Deep Vadose Zone Contamination

Reference PNNL-18661

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management
Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

CH2MHILL
Plateau Remediation Company

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Document Type: TR Program/Project: SGRP

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LE Bratton 2/24/2010
Release Approval Date

Approved for Public Release;
Further Dissemination Unlimited

U.S. DEPARTMENT OF ENERGY

PNNL-18661 Final

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Summary

The U.S. Department of Energy (DOE) and its predecessors released nearly 2 trillion liters (450 billion gallons) of contaminated liquid into the vadose zone at the Hanford Site. Some of the contaminants currently reside in the deeper parts of the vadose zone where they are much less accessible to characterization, monitoring, and typical remediation activities such as removal and disposal. The DOE Richland Operations Office (DOE-RL) prepared a treatability test plan in 2008 to examine remediation options for addressing contaminants in the deep vadose zone; one of the technologies identified was surface barriers (also known as engineered barriers, covers, and caps).

Surface barriers have long been used to isolate contaminants from the accessible environment. In the typical configuration, the contaminants are located relatively close to the surface, generally within 15 m, and thus they are close to the base of the surface barrier. The proximity of the surface barrier under these conditions yielded few concerns about the effectiveness of the barrier at depth, particularly for cases in which the contaminants were in a lined facility. At Hanford, however, some unlined sites have contaminants located well below depths of 15 m, which means that the contaminants are increasingly distant from the surface barrier meant to isolate them from the accessible environment. The issue raised about these sites is the degree of effectiveness of a surface barrier in isolating contaminants in the deep vadose zone. Previous studies by Hanford Site and PNNL researchers suggest that surface barriers have the potential to provide a significant degree of isolation of deep vadose zone contaminants. The studies show that the actual degree of isolation is site-specific and depends on many factors, including recharge rates, barrier size, depth of contaminants, geohydrologic properties of the sediments, and the geochemical interactions between the contaminants and the sediments.

After the DOE-RL treatability test plan was published, Pacific Northwest National Laboratory was contracted to review the information available to support surface barrier evaluation for the deep vadose zone, identify gaps in the information and outcomes necessary to fill the data gaps, and outline tasks to achieve those outcomes. Full understanding of contaminant behavior in the deep vadose zone is constrained by four key data gaps: limited access; limited data; limited time; and the lack of an accepted predictive capability for determining whether surface barriers can effectively isolate deep vadose zone contaminants. Activities designed to fill these data gaps need to have these outcomes:

- *common evaluation methodology* that provides a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above deep vadose zone contamination
- *deep vadose zone data* that characterize the lithology, the spatial distribution of moisture and contaminants, the physical, chemical, and biological process that affect the mobility of each contaminant, and the impacts to the contaminants following placement of a surface barrier
- *subsurface monitoring* to provide subsurface characterization of initial conditions and changes that occur during and following remediation activities
- *field observations* that span years to decades to validate the evaluation methodology.

A set of six proposed tasks was identified to provide information needed to address the above outcomes. The proposed tasks are:

1. **Evaluation Methodology**. Develop common evaluation methodology that will provide a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above deep vadose zone contamination.
2. **Case Studies**. Conduct case studies to demonstrate the applicability of the common evaluation methodology and provide templates for subsequent use elsewhere. Three sites expected to have conditions that would yield valuable information and experience pertinent to deep vadose zone contamination were chosen to cover a range of conditions. The sites are BC Cribs and Trenches, U Plant Cribs, and the T Farm Interim Cover.
3. **Subsurface Monitoring Technologies**. Evaluate minimally invasive geophysical approaches for delineating subsurface plumes and monitoring their migration in the deep vadose zone.
4. **Controlled Field Test at Sisson and Lu Site**. Evaluate the ability of the model to predict long-term liquid, vapor, and chemical transport processes at a well-characterized site containing a plume of subsurface water and tracer remaining from injections in the early 1980s and 2000s.
5. **Deep Vadose Zone Monitoring at T Farm**. Demonstrate the ability of the geophysical sensors and the model to detect and predict long-term migration of liquid and vapor between the vadose zone beneath the infiltration area and the vadose zone protected by the interim cover.
6. **Deep Vadose Zone Monitoring at the Prototype Hanford Barrier**. Demonstrate the ability of geophysical sensors and the model to detect and predict the hydrologic conditions in the vadose zone beneath the Prototype Hanford Barrier 15 years after construction.

Acknowledgments

We extend our appreciation to the external reviewers, including Mark Benecke and Glenn Chronister of CH2M HILL Plateau Remediation Company, Will Nichols of INTERA Inc., and Kevin Leary of the DOE Richland Operations Office. At PNNL, our thanks go first and foremost to Mike Truex, the project manager, for shepherding the initial report concept and outline development and for conducting the peer review. We thank Andrea Currie for editing the report expertly and with patience. We also thank Nathan Johnson for the conceptual model graphics, Duane Ward for the Geographic Information System-based graphics used in Section 2, and Kathy Neiderhiser for the final text processing

Acronyms and Abbreviations

ARAR	applicable or relevant and appropriate requirement
CA	Closure Assessment
CERCLA	*Comprehensive Environmental Restoration, Compensation, and Liability Act of 1980*
CHPRC	CH2M HILL Plateau Remediation Company
CRF	concentration reduction factor
DOE	U.S. Department of Energy
EM	DOE Office of Environmental Management
EPA	U.S. Environmental Protection Agency
FIR	Field Investigation Report
FLTF	Field Lysimeter Test Facility
HDW-EIS	Hanford Defense Waste Environmental Impact Statement
MCL	maximum contamination level
PHB	Prototype Hanford Barrier
RAG	remedial action goal
RCRA	*Resource Conservation and Recovery Act of 1976*
RFI	RCRA Facility Investigation
SAC	System Assessment Capability
SST	single-shell tank
STOMP	Subsurface Transportation over Multiple Phases
TDF	time delay factor
TI	technical impractibility
TPA	Tri-Party Agreement (*Hanford Federal Facility Agreement and Consent Order*)
WMA	waste management area

Contents

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Table

1.0 Introduction

The U.S. Department of Energy Richland Operations Office (DOE-RL) identified several locations at the Hanford Site where significant quantities of contaminants may be situated deep within the vadose zone (DOE-RL 2008). Surface barriers are one of the remediation options available for isolating deep vadose zone contaminants so that groundwater is protected. The effectiveness of surface barriers is highly dependent on the complex interaction of site conditions, surface barrier design and performance features, and vadose zone contaminant conditions. To assist DOE-RL in evaluating the effectiveness of surface barriers for protecting groundwater, the Pacific Northwest National Laboratory prepared this report for CH2M HILL Plateau Remediation Company, the Hanford Site contractor for Central Plateau remediation.

The purpose of this document is to present a strategy for evaluating the effectiveness of surface barriers for site-specific deep vadose zone remediation. The strategy provides a technically defensible approach to determine the depth to which a surface barrier can effectively isolate contaminants in the vadose at a specific site as a function of subsurface properties, contaminant distribution, barrier design, and infiltration control performance. The strategy also provides an assessment of additional data and information needs with respect to surface barrier performance for deep vadose zone applications. The strategy addresses the linkage between surface barriers and deep vadose zone in situ remediation activities, monitoring issues, and emerging science, technology, and regulatory objectives. In short, the report documents the existing knowledge base, identifies knowledge needs (based on data gaps), and suggests tasks whose outcomes will address those knowledge needs. More important, the report serves as a starting point to engage the regulator and stakeholder community on the viability of deploying surface barriers for deep vadose zone contamination. As that engagement unfolds, a systematic methodology can be formalized and instituted.

The strategy is focused on deep vadose zone contamination and the methods needed to determine the impact to groundwater from those deep vadose zone contaminants. Processes that affect surface barrier performance, recharge in the areas surrounding the surface barrier, and the near-surface vadose zone beneath the barrier are acknowledged but are not addressed by this strategy. In addition, the collection of site-specific data on contaminant distribution and geologic structure and properties are programmatic responsibilities and are not provided by this strategy.

Section 2 of this report identifies deep vadose zone contamination problems and describes surface barriers and the objectives of their use in solving those problems. Section 3 presents the strategy necessary to deploy surface barriers for protecting groundwater from contaminants in the deep vadose zone. Section 4 summarizes the existing information that can satisfy some of the strategic elements discussed in Section 3. Section 5 identifies six tasks designed to provide methods and data to satisfy key knowledge gaps such that surface barriers can be accepted as a viable solution and successfully deployed at sites for which they are appropriate.

2.0 Problem Definition

At several Hanford waste sites in the Central Plateau, significant quantities of contaminants are known or expected to be located in the deep vadose zone where remediation techniques other than physical removal need to be considered. Remediation technologies under consideration would address contamination by reducing the flux of contaminants to groundwater to meet remediation goals associated with protection of human health and the environment. Some of the remediation approaches include or require control of surface water infiltration. The primary method for controlling infiltration is through the deployment of a surface barrier. This section identifies sites that may have deep vadose zone contamination, describes a surface barrier and illustrates some typical designs, and provides an example of how a surface barrier affects the travel time between the vadose zone and groundwater.

2.1 Deep Vadose Zone Contamination

DOE-RL (2008) examined the available information on potential deep vadose zone contamination of technetium and uranium in partial fulfillment of Tri-Party Agreement (TPA) Milestone M-015-50, *Submit a Treatability Test Work Plan for Deep Vadose Zone Technetium and Uranium to Ecology and EPA* (Ecology et al. 1989). The available information included disposal inventories, depth of contamination, and potential risk to groundwater (Eslinger et al. 2006). Although the information sources have large uncertainties, DOE-RL (2008) was able to identify specific sites that potentially contained significant quantities of technetium-99 and uranium in the deep vadose zone such that they merit consideration for some form of remediation to protect groundwater. The sites are grouped in Table 2.1 according to contaminant.

Table 2.1. Deep Vadose Zone Sites Containing Technetium-99 and Uranium

Site	Example
Technetium-99	
BC cribs and trenches	216-B-14, -18
BY cribs and vicinity	216-B-46, -49
T Tank Farm and vicinity	241-T-106
S/SX tank farms and vicinity	241-SX-108
Uranium	
200 East Ponds region	216-A-19
U cribs	216-U-1, -2, -8, and -12
B Plant cribs and trenches	216-B-12
B, BX, BY tank farms	241-BX-102
PUREX[a] cribs and trenches	216-A-4, -3, -9
REDOX[b] cribs and trenches	216-S-7, -1 and 2

(a) Plutonium-Uranium Extraction Plant.
(b) Reduction and Oxidation Plant.

All of the sites can be grouped into a deep vadose zone region on the Central Plateau. Figure 2.1 shows the location of the deep vadose zone region relative to other Hanford Site features, including the Columbia River. Figure 2.2 shows the location of the sites within the deep vadose zone region that were identified by DOE-RL (2008) as potentially containing significant quantities of contaminants in the deep vadose zone.

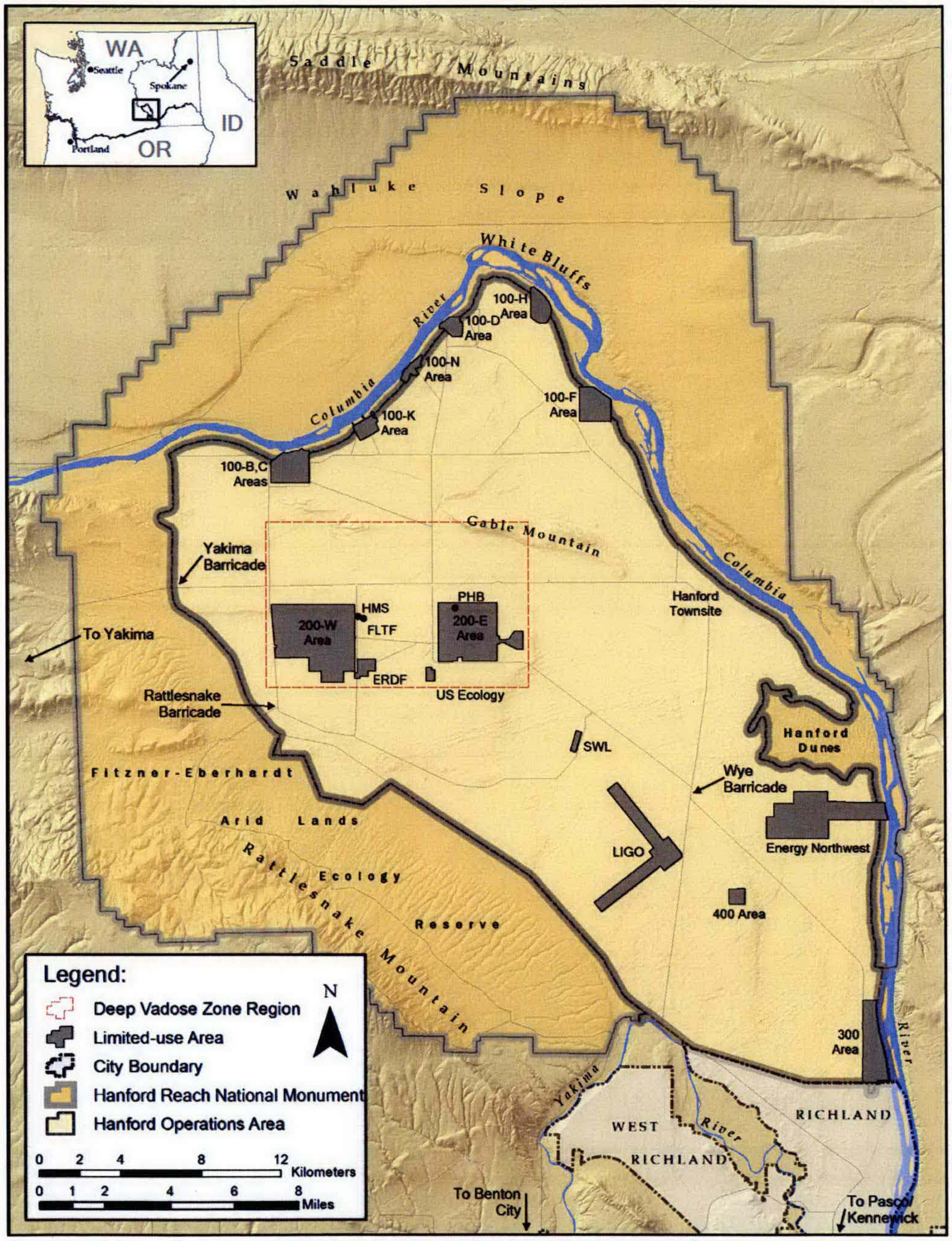


Figure 2.1. Central Plateau and Other Hanford Site Features. The deep vadose zone region is a rectangular area large enough to encompass the sites identified in Table 2.1.

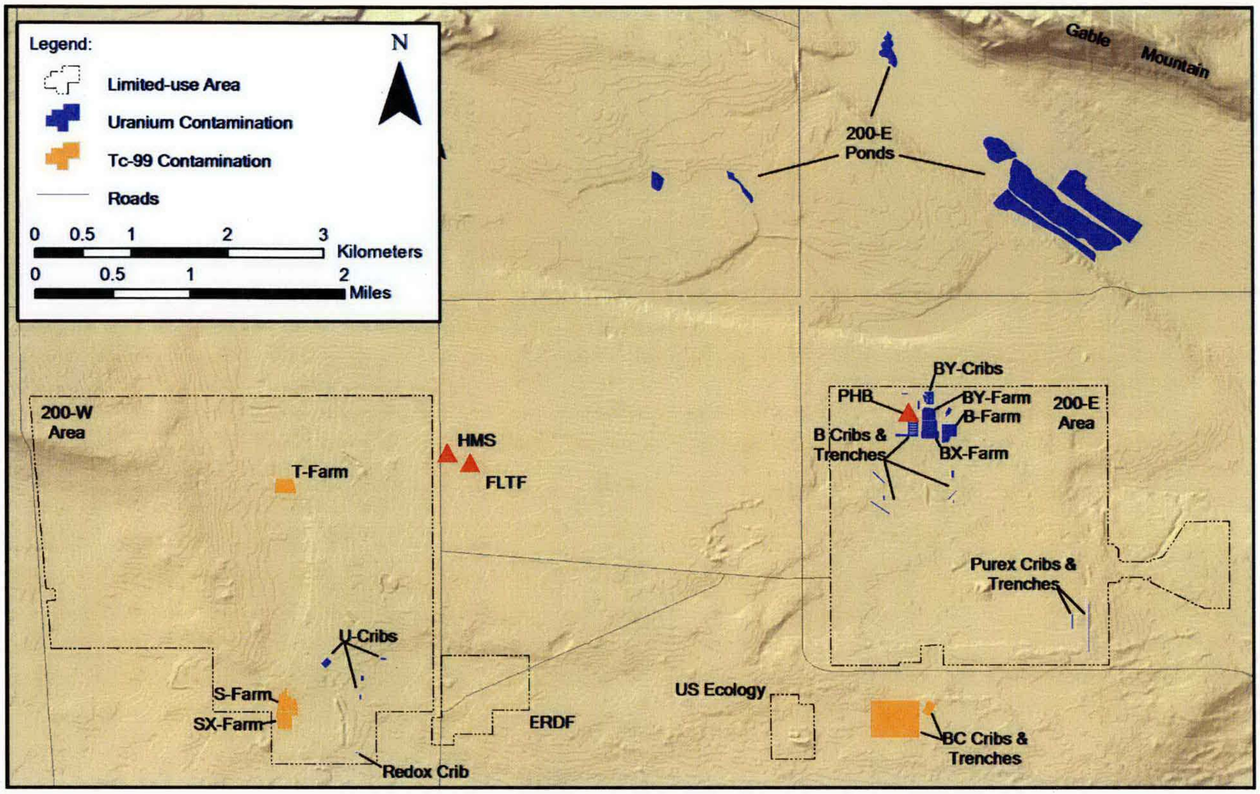


Figure 2.2. Sites on the Central Plateau with Potentially Significant Deep Vadose Zone Contamination (DOE-RL 2008)

2.2 Surface Barriers

Surface barriers are earthen or manufactured covers placed on the soil surface above subsurface contaminants. The reasons to use surface barriers include limiting water infiltration (to reduce contaminant migration), preventing plant and animal intrusion, and limiting water runoff and gaseous emissions. In addition to these performance goals, surface barriers are expected to be durable such that they resist degradation processes such as wind and water erosion. Figure 2.3 shows conceptually a surface barrier above a deep vadose zone contamination plume.

Surface barriers have been studied at Hanford since the mid 1980s. A research and development effort begun in 1985 culminated in a barrier development plan (Wing 1994) that included the following objectives:

- Limit recharge to 0.5 mm/yr.
- Require no maintenance.
- Minimize plant, animal, and human intrusion, exhalation of gases, and erosion impacts.
- Meet or exceed *Resource Conservation and Recovery Act of 1976* (RCRA) cover performance requirements.
- Isolate waste for a minimum of 1,000 years.
- Be regulatorily and publicly acceptable.

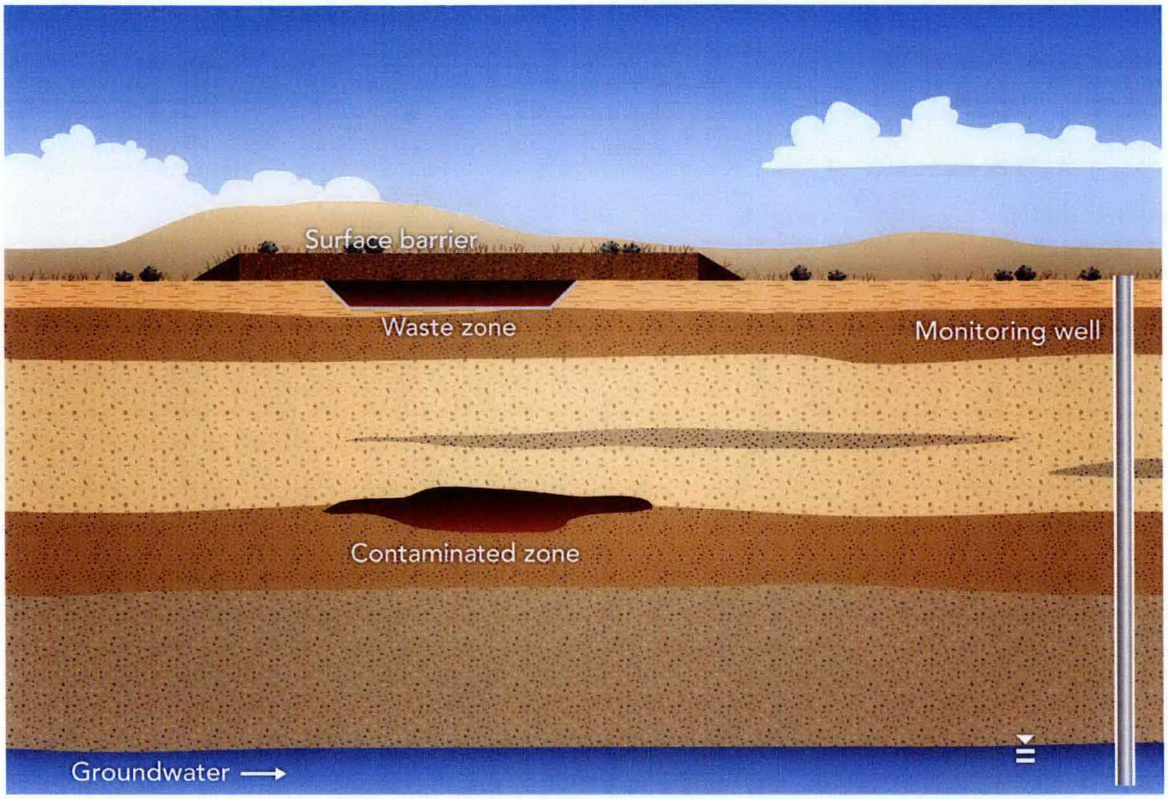


Figure 2.3. Conceptual Model of Surface Barrier, Vadose Zone, and Groundwater

Figure 2.4 shows a cross section of the functional portion of the barrier (sans side slopes), which Wing (1994) called the "permanent isolation surface barrier."

Shortly thereafter, DOE conducted a study of surface barrier needs at the Hanford Site, realizing that not all waste sites required the rigorous protection afforded by the design in Wing (1994). The result was four designs, each with a set of functional criteria related to the level of protection needed for specific waste sites. The most protective barrier, called the Hanford Barrier, is essentially identical to the barrier design evaluated by Wing (1994). In decreasing levels of protection, the remaining three designs are the modified RCRA Subtitle C barrier, the standard RCRA Subtitle C barrier, and the modified RCRA Subtitle D barrier. Figure 2.5 shows cross sections of each design (sans side slopes).

During the same timeframe, the Barrier Development Program (Wing 1994) built a full-scale prototype of the Hanford Barrier over the 216-B-57 crib as part of a *Comprehensive Environmental Response, Compensation, and Liability Act of 1980* (CERCLA) treatability study (DOE-RL 1999). What makes this barrier unique is that two side slope designs were included in the study—a 1V:10H sandy gravel side slope and a 1V:3H basalt riprap side slope. Figure 2.6 shows a cross section of the functional portion of the barrier as well as the two side slope designs.

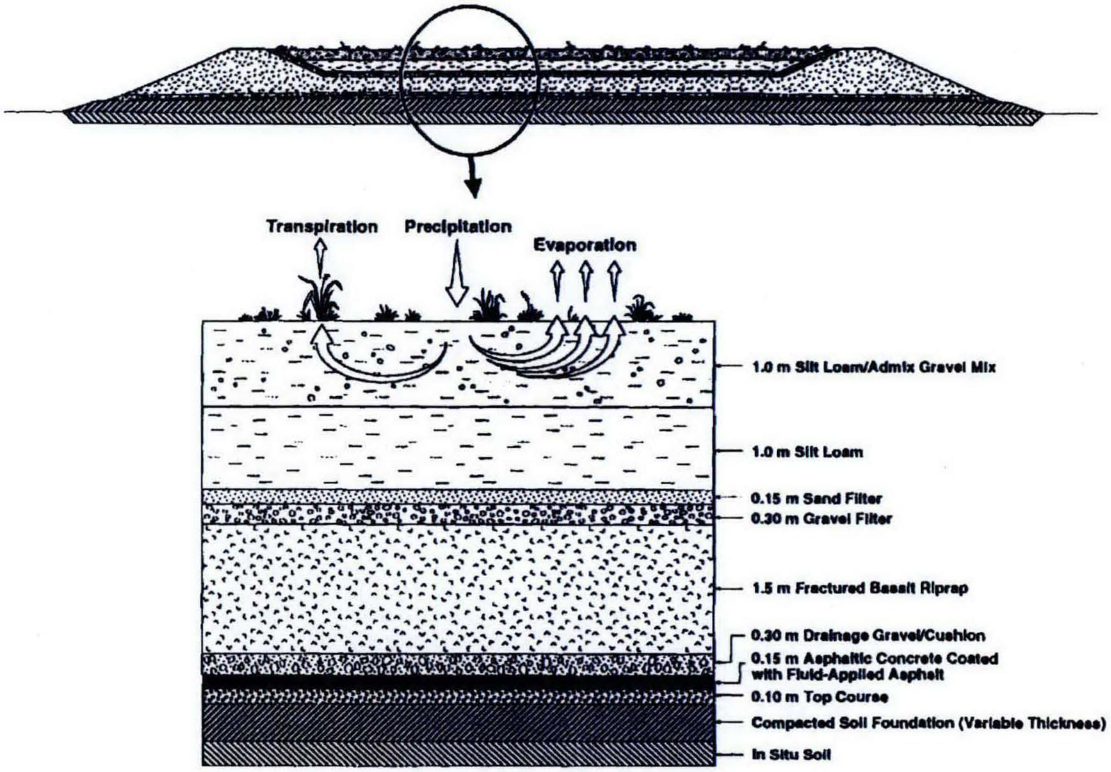


Figure 2.4. Hanford Barrier Design (after Wing 1994)

During the same time that surface barriers were being designed and developed at the Hanford Site, surface barrier designs were being studied and tested elsewhere. In the late 1990s, the U.S. Environmental Protection Agency (EPA) started the Alternative Cover Assessment Project in which they conducted field studies of barrier designs at eleven sites around the country (Albright et al. 2004). The studies were conducted in environmental settings that ranged from warm to cold and humid to dry. The designs tested by the Alternative Cover Assessment Project included conventional RCRA cover designs as well as alternative designs that are "equivalent" to the conventional RCRA design. The alternative designs typically employed evapotranspiration to achieve equivalency, thus their performance depended on site-specific plant cover and soil thickness and properties. Some of the alternative designs employed a capillary break layer to increase soil water storage near the soil surface and enhance evapotranspiration. The Hanford Barrier design includes a capillary break.

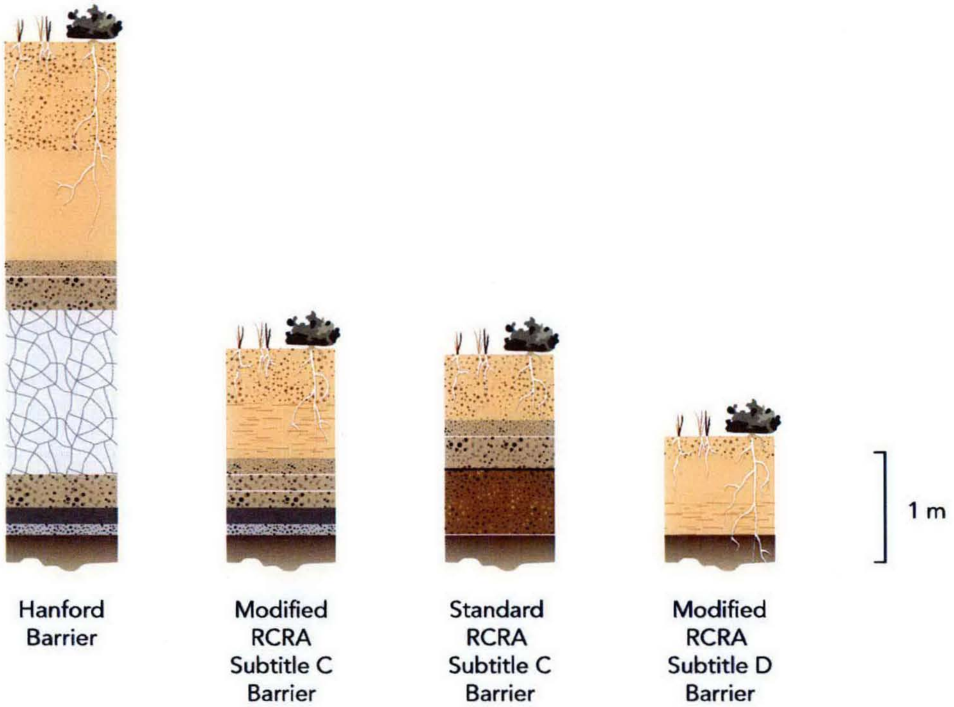


Figure 2.5. Barrier Designs Considered in Focused Feasibility Study (after DOE-RL 1996). Individual layers represent different material types. The depth of plant roots approximates the expected zone of plant water withdrawal.

2.3 Impact of a Surface Barrier on Travel Time

A computer simulation using the Subsurface Transport over Multiple Phases (STOMP) program (White and Oostrom 2006) was executed to demonstrate the potential impact that a surface barrier could have on subsurface travel times to the water table. The conceptual model was chosen to be homogeneous and isotropic to highlight the impacts of a surface barrier without the additional complexity that might be caused by subsurface heterogeneities. In this simple example, the two-dimensional domain was loosely based on the barrier simulations reported by Piepho and Benecke (2007). The domain extended 420 m in the horizontal and 110 m in the vertical direction. The water table was located 104 m below the ground surface, which yielded a saturated zone thickness of 6 m. The material properties were as described by Piepho and Benecke (2007). The barrier recharge rate was 0.5 mm/yr. The lateral boundaries in the vadose zone were specified as no-flow boundaries.

Unlike the simulations presented in the Piepho and Benecke report, the simulations conducted for this report used a uniform grid discretization of 1 m in both the horizontal and vertical directions. At and below the water table, a hydrostatic pressure distribution was assigned at the boundaries, assuming an easterly groundwater flow gradient of 2.5×10^{-4} m/m. The upper boundary condition of the simulation domain was specified with a recharge rate of 3.5 mm/yr in the area surrounding the surface barrier. Because the solution is steady-state, the impacts of initial conditions and the transient effects of barrier emplacement were not considered.

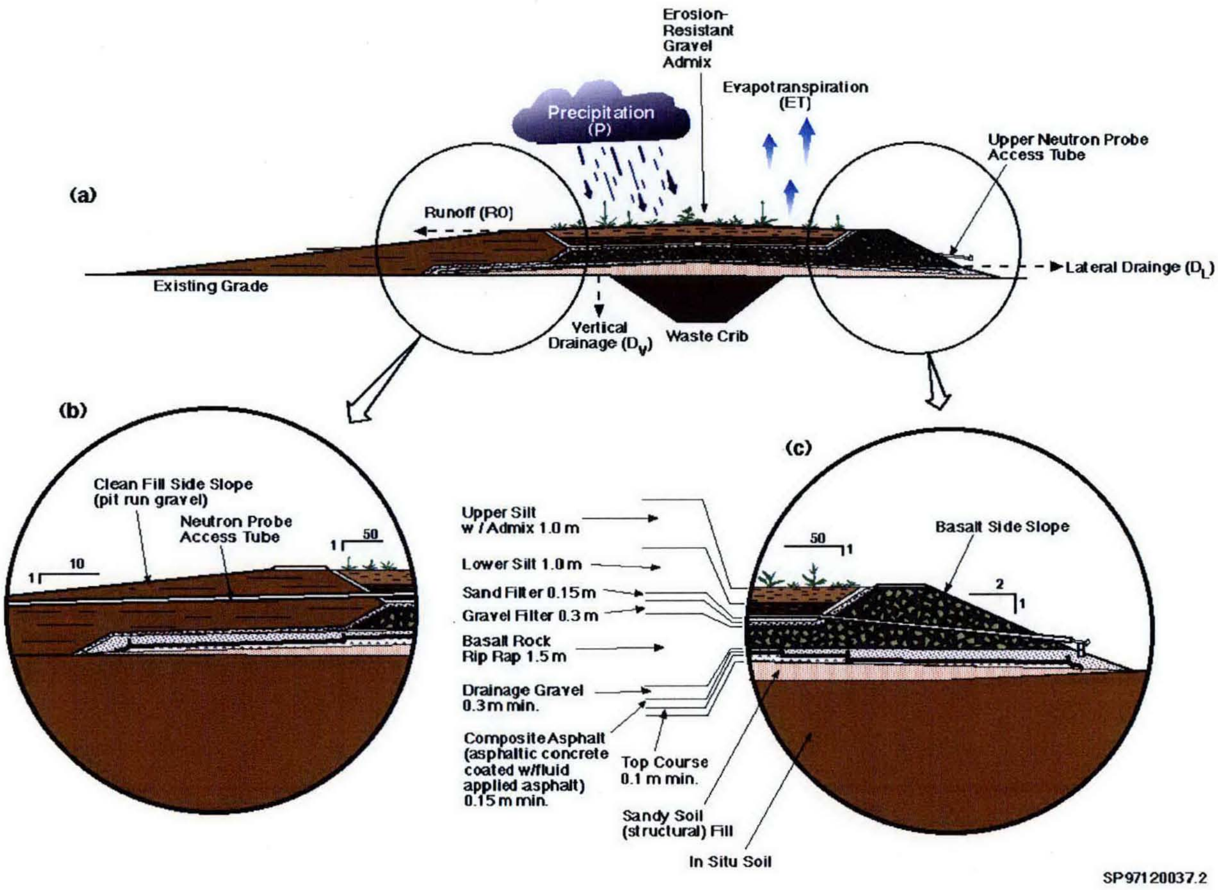
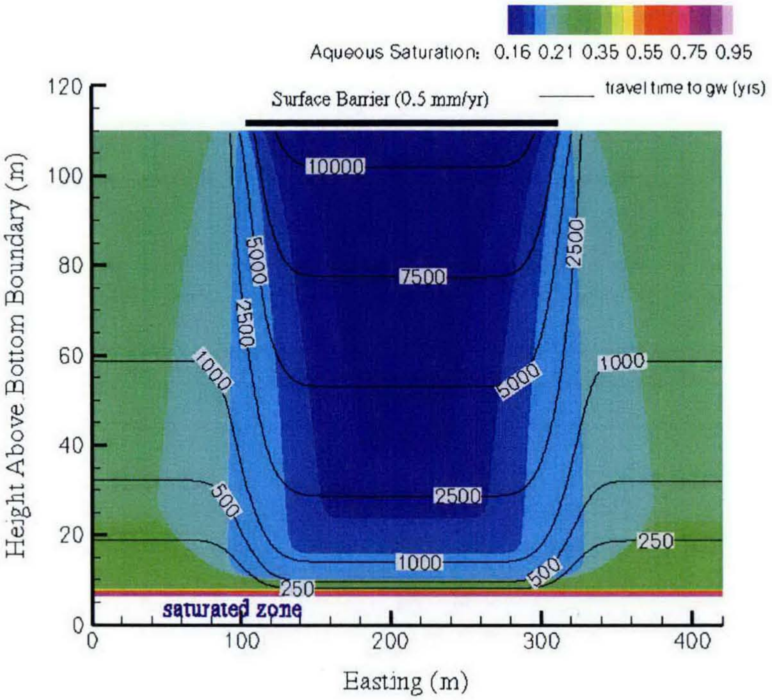


Figure 2.6. Prototype Hanford Barrier Design (reproduced from Gee et al. 2002, p. 2.2, Figure 2.2)

The simulation was executed until a steady-state flow condition was obtained, at which time particle tracking was performed using MODPATH Version 4.2 (Pollock 1994). This was accomplished by writing grid, hydraulic head, velocity, and boundary data to input files required by MODPATH. Particles were placed at every grid cell to obtain a travel time to the groundwater surface. These travel times represented the time needed for a conservative (i.e., nonsorbing, nonreacting, nondecaying) contaminant to reach the water table with the steady-state flow field. Transient impacts caused by the reduction in recharge following placement of the barrier were not considered. Diffusion and dispersion were also not considered, as particle tracking uses advective velocities to compute trajectories and travel times.

Figure 2.7 (top) shows the lateral and vertical extent of the impact of a surface barrier on the degree of saturation in the steady-state velocity field. Near the surface, saturations range from 15% immediately beneath the surface barrier to 21% at the edges of the domain. Beneath the center of the barrier, the saturation remains below 16% as deep as 90 m, whereas saturations near the lateral boundaries are more than 20%. In the absence of a surface barrier, saturations would be uniformly approximately 21% throughout most of the vadose zone (Figure 2.7, bottom).



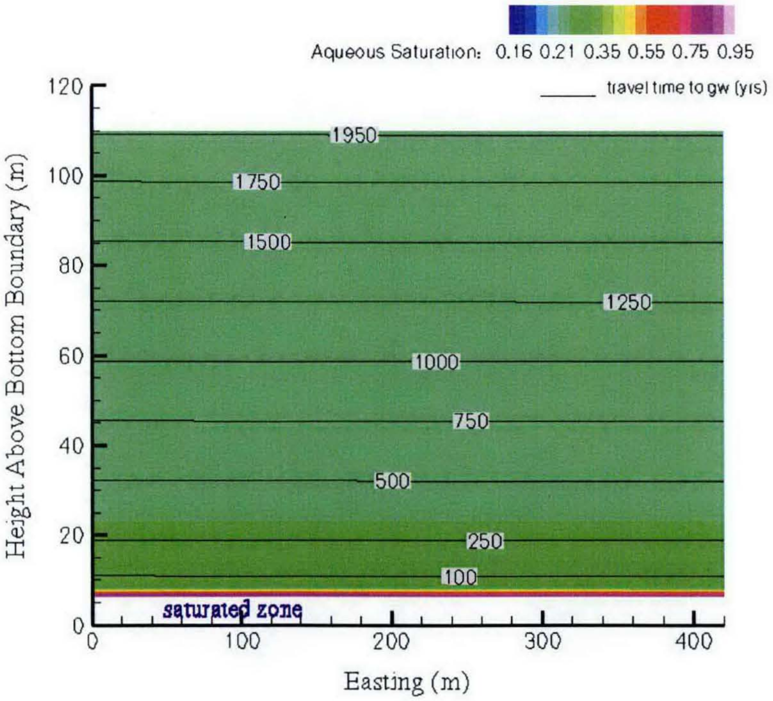


Figure 2.7. Steady-State Saturation Distribution and Travel Times for a Two-Dimensional Domain (top) with a Surface Barrier and (bottom) Without a Surface Barrier

The top panel of Figure 2.7 also shows the lateral and vertical extent of the impact of a surface barrier on travel times. Directly beneath the barrier, where the impact of the barrier was greatest, travel times for the steady-state velocity field were more than 10,000 years. At the same depth less than 100 m beyond the edge of the barrier, the travel times to the water table were closer to 1,950 years. Although travel times were impacted most significantly below the center of the surface barrier, the barrier impact on travel time extended nearly 30 m beyond the barrier edge. A similar effect (i.e., changes in the vadose zone outside the edge of the barrier) was noted by Bauer (2007) in a study of the potential impact of an interim barrier at T Farm.

In summary, a simple two-dimensional simulation was conducted to demonstrate the impact of a surface barrier on travel times within a homogeneous isotropic vadose zone. The results illustrate that the surface barrier increases travel time and that the increase is a function of depth and a function of distance from the barrier edge. The results also show that the surface barrier increases travel times in the vadose zone for some distance beyond the barrier edge.

3.0 Evaluation Methodology Background

A successful evaluation methodology provides the information necessary to support a CERCLA feasibility study assessment of appropriate surface barrier deployment for protection of the deep vadose zone. DOE-RL (2008) briefly summarized the actions necessary for surface barrier evaluation, and those actions are provided below. This section expands and elaborates on the actions.

3.1 Surface Barrier Evaluation Guidance

There are many surface barrier guidance documents and research reports and papers. Recent publications relevant to the Hanford Site today are the DOE-RL treatability test plan (DOE-RL 2008) and two National Research Council (Council) committee reports (Council 2007 and Council 2009) Each is discussed below.

The *Deep Vadose Zone Treatability Test Plan for the Hanford Central Plateau* identified surface barriers as a key potential technology for use alone or in combination with in situ technologies to isolate contaminants in the deep vadose zone (DOE-RL 2008). Section 4.2.6 of the test plan outlined the objectives that an assessment of surface barriers should have and identified the need for the following activities:

- Determine how deep the effect of surface infiltration control extends into the vadose zone as a function of the areal extent of the surface barrier, including side slopes.
- Determine the impact of surface infiltration control on water and technetium-99 and uranium already located in the deep vadose zone.
- Identify the constituents and/or conditions that should be monitored to assess barrier impact on the deep vadose zone.
- Identify monitoring systems that can provide data on changes in the baseline conditions for the long-term application necessary for the deep vadose zone applications.
- Link performance of the barrier in the deep vadose zone to barrier performance elements.

The National Research Council examined the overall topic of assessing the performance of engineered barriers, of which surface barriers are one example (Council 2007). In that report, two observations relevant to Hanford concern barrier lifetime and performance monitoring:

1. **Lifetime**. The existing sets of performance data can support predictions of long-term performance, but those predictions will have high uncertainties that may not be significantly reducible until field data are collected "for longer periods, perhaps up to 100 years or more." The Council stated that the "development of designs for lifetimes of thousands of years is likely to be both infeasible and prohibitively expensive" and that "designs that allowed for recovery, repair, and/or replacement should be encouraged."
2. **Performance Monitoring**. The thrust of the report is the performance of the surface barrier; there is no real mention of deep vadose challenges of the type seen at Hanford. Regardless, the Council noted that monitoring should include a variety of monitoring techniques in all significant media (e.g.,

surface water; air; soil). The Council also noted the value of geophysical and remote sensing techniques.

Relevant to the observation of barrier lifetime, the Council report (Council 2007) referred to analogues but did not discuss or elaborate on the value of analogues for assessing the long-term performance of surface barriers. The Barrier Development Program (see Section 2.2) conducted studies to examine natural analogues relevant to evaluation of the long-term performance of barriers (Wing 1994). The topics examined included geologic outcrops similar to barrier components, armored-surface analogues, pedogenic indicators of soil water movement, geofilters, plant community dynamics, ancient mounds, asphalt analogues, and long-term climate change. The information on analogues collected by the Barrier Development Program could strengthen the assessment of surface barrier durability and provide a more defensible estimate for barrier longevity at the Hanford Site.

The Council's 2007 report provided a set of recommendations to improve the assessment of engineered barriers. Although the recommendations are targeted at surface barriers, they easily can be applied to the deep vadose zone. The recommendations include the following:

- Monitoring programs should collect data needed to assess the long-term performance of engineered barriers.
- Regulatory agencies should develop guidelines to increase direct monitoring of barrier systems and their components.
- Federal agencies should assess performance on a regular basis (e.g., once every 5 to 10 years) and place the results in the public domain in a readily-accessible form.
- Federal agencies should use field observations and measurements to validate, calibrate, and improve models to predict the behavior of engineered barriers over long periods of time.
- The EPA and the U.S. Nuclear Regulatory Commission should develop guidance for the practical implementation of performance-based criteria for assessment of containment system performance as an alternative to prescriptive designs.

The DOE Office of Environmental Management (DOE-EM) asked the National Research Council to provide advice to DOE-EM regarding the cleanup technology roadmap. Part of the Council's mandate was to identify the key science and technology gaps and their priorities for the cleanup program. Relative to the Groundwater and Soil Remediation program area, the Council identified the following gaps and assigned priorities (Council 2009):

- The behavior of contaminants in the subsurface is poorly understood (high priority).
- The long-term ability of cementitious materials to isolate wastes is not demonstrated (high priority).
- Site and contaminant source characteristics may limit the usefulness of EM's baseline subsurface remediation technologies (medium priority).
- The long-term performance of trench caps, liners, and reactive barriers cannot be assessed with current knowledge (medium priority).

Recognizing that sufficient fundamental knowledge and technology to complete the cleanup mission were not yet completely within DOE's grasp, the Council provided a research recommendation to bridge the gap. Elements of that recommendation pertinent to the evaluation of surface barrier protection of groundwater from deep vadose zone contamination are

- radiochemistry of EM wastes and contaminants
- long-term performance of cementitious materials
- retrieval technology for high-level waste
- alternative and advanced waste forms and production methods
- long-term behavior of in-ground contaminants
- advanced sensors, detectors, and data transmission technology for subsurface monitoring
- advanced near-surface engineered barrier systems to control contaminant release to the environment.

In reference to near-surface barrier systems, the Council noted that "the design of such barriers is heavily dependent on local climate and subsurface conditions, and EM and its contractors need extensive knowledge of both" (Council 2009).

3.2 Proposed Components of a Barrier Evaluation Methodology for the Deep Vadose Zone

Subsurface evaluation strategies for near-surface contaminated sites are reasonably well developed and have been used extensively to support cleanup. Sampling is relatively easy, a single remediation option is often sufficient, and the outcome can be quantified fairly quickly in downgradient groundwater wells. In contrast, deep vadose zone contamination is difficult to characterize and monitor; may require multiple remediation options involving a combination of physical, chemical, and biotic changes; is spread over a much larger domain; and may not be detected in groundwater for centuries to millennia. The challenges are extensive enough to require that the normal evaluation strategy be expanded to address issues specific to deep vadose zone contamination.

Listed below are the components of a barrier evaluation methodology for assessing surface barrier protection of groundwater from deep vadose zone contaminants. The outcomes are credible predictions of surface barrier impacts, acceptance of those predictions by stakeholders, and actionable results that can support setting functional design requirements for surface barriers.

a. *Define Design Guidance* for Surface Barriers to Protect Deep Vadose Zone Contamination and Prevent Exceedence of Maximum Contamination Levels (MCLs) in the Groundwater
    i. Identify existing regulatory requirements and supporting information (e.g., applicable or relevant and appropriate requirements [ARARs]; remedial action goals [RAGs]).
    ii. Establish functional design requirements.
b. *Identify Other Site-Specific Remedial Activities*
    i. Spatial and temporal impacts to the conceptual model
    ii. Performance monitoring requirements
c. *Identify the Recharge Conceptual Model.* Identify the design elements that are relevant to recharge beneath and around a surface barrier. In addition to traditional barrier design elements,

the following design considerations are of particular significance in determining the impact of a barrier on the deep vadose zone:

i. recharge rate beneath the functional portion of the barrier
ii. position of the edge of the functional portion of the barrier relative to the underlying contaminated zone
iii. recharge rate beneath the transition zone that separates the functional portion of the barrier from the surrounding terrain
iv. design standard for side slopes
v. off-barrier storage of runoff and diverted percolation
vi. recharge rates in the vicinity of the barrier (e.g., spatial distribution of natural rates; facility-induced rates; roads)
vii. time-dependent potential changes in recharge rates as the barrier and surrounding terrain change and as associated ecological communities evolve.

Figure 3.1 illustrates conceptually the surface conditions that can affect recharge rates beneath and around a surface barrier. Not all features displayed in Figure 3.1 will necessarily be relevant at a particular site; conversely, it is possible that features not displayed in Figure 3.1 will be present. The important point for a site-specific application of a surface barrier is to evaluate the surface conditions that are applicable at that site.

d. *Identify the Deep Vadose Zone Conceptual Model.* Identify the site properties and conditions that impact the applicability of surface barriers to the deep vadose zone:

i. geologic lithology and structures that create alternate flow and transport pathways (e.g., sloped layers; clastic dikes)
ii. site-specific physical, hydraulic, thermal, and geochemical properties for each lithologic unit and for the contamination zone
iii. deep layer sequences that may limit downward migration of water and contaminants (e.g., local capillary breaks)
iv. nature of the contaminated zone (e.g., depth to top and bottom; lateral extent; distance between the bottom of the contaminated zone and groundwater; variability of contamination within the contaminated zone)
v. spatial distribution of vadose zone water content when barrier is emplaced
vi. groundwater depth and flow direction when barrier is emplaced
vii. evolution of vadose zone conditions (e.g., hydraulic; geochemical; thermal; biotic) during the lifetime of the barrier
viii. potential changes in groundwater depth and flow direction during barrier lifetime (e.g., increase in upgradient irrigation; Hanford pump-and-treat operations)
ix. evolution of radionuclide daughter products and associated physical and chemical properties.

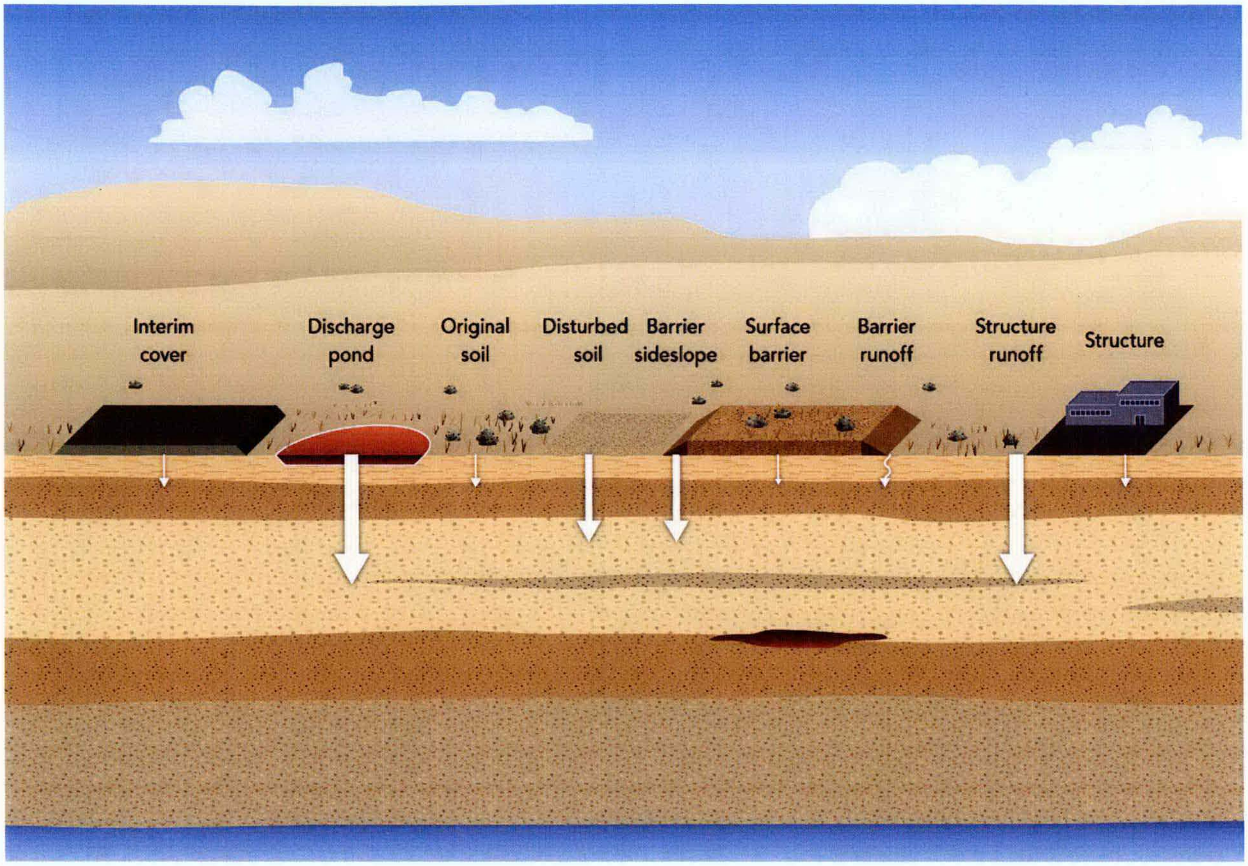


Figure 3.1. Conceptual Model of Potential Recharge Conditions Associated with a Surface Barrier and Its Surroundings

Figure 3.2 illustrates conceptually the subsurface conditions that can affect contaminant fate and transport in the vadose zone beneath a surface barrier. Not all conditions displayed in Figure 3.2 will necessarily be relevant at a particular site; conversely, it is possible that features not displayed in Figure 3.2 will be present. The important point for a site-specific application of a surface barrier is to evaluate all potential subsurface conditions applicable beneath that site.

e. *Identify Design and Assessment Tool Requirements*

   i. Confirm/quantify the assessment efficacy for each unique condition. Address relevant subsurface geologic structure and lineation and the variability of material properties, especially at the interface of different lithologic layers.

   ii. Address in all dimensions the processes that affect contaminant behavior in the deep vadose zone (e.g., water movement under low-moisture conditions; flow induced by osmotic potential gradients; flow induced by thermal gradients; diffusion of water and contaminants; microbial activity; geochemical precipitation/dissolution).

   iii. Address release history (e.g., BC cribs and trenches show significant differences in distributions from trenches and cribs).

   iv. Address the impact of remediation activities (e.g., desiccation).

   v. Address response to major surface disturbances (e.g., precipitation; fire).

vi. Select numerical models (e.g., flow; transport; geophysics) that are consistent with the conceptual model defined in Steps c and d above to predict the fate and transport of contaminants. Consider model reduction if warranted based on prior experience.

vii. Identify initial conditions consistent with release history and surface and subsurface conditions.

viii. Specify boundary conditions that honor the relevant processes and conditions.

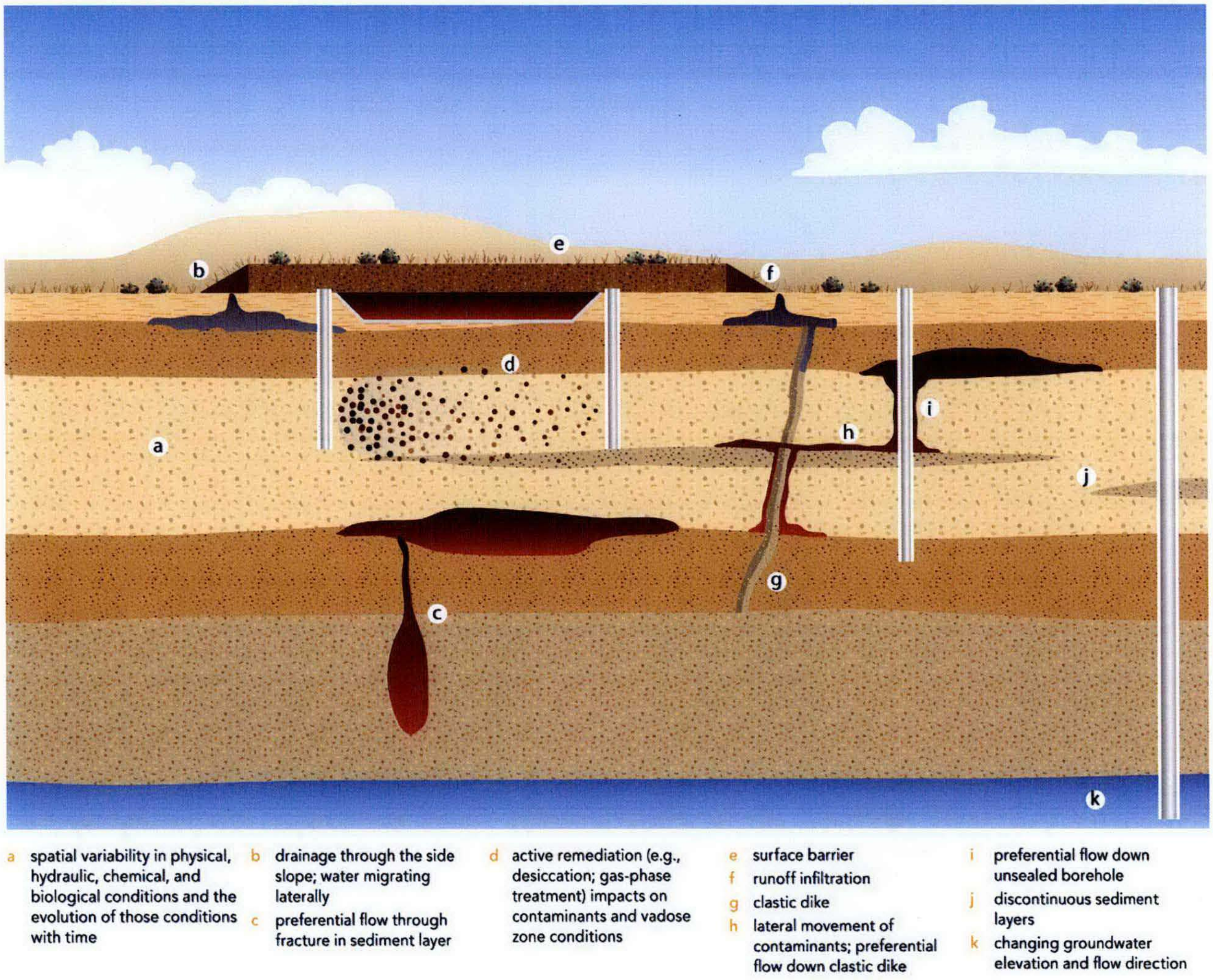


Figure 3.2. Conceptual Model of Hydrologic, Geochemical, Geologic, and Biotic Conditions Associated with the Deep Vadose Zone. All major processes are illustrated for convenience. This figure does not represent a specific site nor does it imply any degree of probability that all processes illustrated will be found at one location.

f. *Identify Relevant Field Data* to Address Assessment Requirements for Deep Vadose Zone Applications
    i. model evaluation and testing data (e.g., initial conditions; distribution of contaminant concentrations in the vadose zone)
    ii. surface barrier-vadose zone data (e.g., barrier performance data; analogues; boreholes; geophysics)
    iii. recharge rates beneath barrier side slopes, in natural settings surrounding barriers, and in disturbed areas
    iv. future changes in recharge rates in areas surrounding barriers as those areas evolve to a more natural condition following closure and major disturbances (e.g., loss of vegetation due to wildfire)
    v. upper-bound recharge rates for barrier design (e.g., thickness of silt-loam layer) that account for events such as climate change and extreme storms (e.g., 500-year storm event)
    vi. impacts of episodic events (e.g., rapid snow melt) on recharge and the movement of vadose zone contaminant plumes to the groundwater.

g. *Identify Monitoring Requirements* for Validation, Performance, and Compliance
    i. Detect and delineate deep vadose zone contaminant distributions (spatial changes).
    ii. Quantify deep vadose zone contaminant fate and transport processes (temporal changes).
    iii. Install, maintain, and retrieve deep vadose zone sensors.
    iv. Provide reliable and accurate monitoring tools and redundant systems to extend life expectancies for nonretrievable elements and provide contingency for predicted future instrument failure.
    v. Increase spatial and/or temporal resolution.
    vi. Increase zone of influence of point sensors.
    vii. Automate detection of changes in state variables (e.g., water content, matric potential, temperature) or surrogates (e.g., resistivity, dielectric permittivity, streaming potentials) under normal and hypersaline conditions.
    viii. Maximize use of remote sensing techniques (e.g., cameras; unmanned aerial vehicle; aircraft; satellite) for long-term monitoring of surface barriers to support development of relevant measures of barrier performance and to assess impact.

h. *Evaluate Iteratively and Transparently*
    i. Compare predictions with monitoring data to improve conceptual models and increase the defensibility of predictions of the fate and transport of deep contaminants. Consider model reduction after each iteration.
    ii. Confirm and quantify the assessment efficacy for each unique condition.
    iii. Identify process and parameter sensitivities.
    iv. Estimate uncertainty of predictions.
    v. Evaluate results relative to expected outcomes and provide feedback to functional design requirements for surface barriers.

4.0 Information Available to Support Surface Barrier Application for the Deep Vadose Zone

A necessary prerequisite to establishing a methodology for evaluating the impact to groundwater from the placement of surface barriers above deep vadose zone contamination is to identify the existing knowledge. Looney and Falta (2000) contains a collection of chapters by nationally recognized experts in vadose and groundwater hydrology. The two-volume set, *Vadose Zone Science and Technology Solutions*, covers vadose zone topics ranging from conceptual models to vadose zone project management, characterization, monitoring, modeling, remediation, and science and technology needs.

The information provided by Looney and Falta (2000) is useful and necessary but does not include the site-specific knowledge needed to make informed decisions at Hanford. This section summarizes some of what is known at Hanford about the evaluation components identified in Section 3. Rather than being an exhaustive review of all material, this section provides enough information to document what is known and identifies gaps in the information that need to be filled in order to execute the strategy effectively.

4.1 Regulatory Context

Environmental protection at DOE facilities is governed by DOE Order 5400.1, which was enacted to "establish environmental protection program requirements, authorities, and responsibilities for DOE operations for assuring compliance with applicable Federal, State and local environmental protection laws and regulations" (DOE 1990). DOE Orders must be followed in addition to any applicable federal and state regulations. Outside of DOE, CERCLA is the key federal regulation designed to protect human health and the environment from hazardous contaminants that have been discharged into the environment (CERCLA 1986). The CERCLA legislation gives the EPA authority to clean up abandoned, significantly contaminated waste sites. At Hanford, the sites that are expected to have significant deep vadose zone contamination are all in or near the 200 Areas. Those areas were placed on the National Priorities List, which designates them to be Superfund sites per CERCLA. The CERCLA legislation allows for removal in the case of emergencies (1-year duration only) and remediation to make the site clean (even if it requires many years). For deep vadose zone sites that are ultimately judged not to be candidates for remediation within current cost and technology constraints, the CERCLA legislation provides an option to seek a technical impracticability (TI) waiver.

According to the DOE Office of Health, Safety and Security (DOE-HSS 2009), CERCLA does not supersede other laws or specify cleanup levels. Instead, CERCLA requires that applicable or relevant and appropriate requirements (ARARs) be used to determine cleanup standards on a site-specific basis. ARARs include federal and state requirements and other agreements such as Federal Facility Agreements. The key agreement at Hanford that governs overall cleanup is the Tri-Party Agreement, or TPA (Ecology et al. 1989). The TPA signatories are the DOE, EPA, and the Washington State Department of Ecology (Ecology).

The decision-making process for remediation of the deep vadose zone could be complicated because the contaminant source sites include both CERCLA and RCRA wastes. For example, site boundaries are well defined spatially, but the depth, breadth, and uncertainty of the deep vadose zone plumes make it difficult to define precise boundaries to distinguish between CERCLA and RCRA plumes. Furthermore, the plumes at some sites may have commingled in the deep vadose zone. The TPA parties recognized this deep vadose zone challenge and asserted that the CERCLA process is "functionally equivalent" to that of the RCRA corrective action process (Ecology et al. 1989; DOE-RL 2008). Therefore, treatability test plans designed to address deep vadose zone contamination can and will satisfy the purpose of both statutory programs.

Another example of how the decision-making process could be complicated is in the establishment of responsibility and authority to take action in cases where plumes are mixed or when a deep vadose zone plume migrates under an unrelated waste site. For the surface waste sites and the groundwater, operable units are established with clear remediation goals. For the deep vadose zone plumes that are commingled or of uncertain origin, that is not the case. The lack of clarity and coordination could lead to closure of surface sites with an appropriate remedy (e.g., a RCRA-equivalent barrier) that could be inadequate for an underlying deep vadose zone plume if that plume would be better remediated by a different, and possibly more protective, remedy. Possible solutions include the creation of "deep vadose zone operable units" or the extension of groundwater operable units upward to include the deep vadose zone, application of remediation technologies, or pursuit of a TI waiver.

The technical aspects of regulatory requirements include characterization, surface barriers, and groundwater monitoring. All three have become well defined through years of experience across the nation. There is plenty of experience at the Hanford Site in meeting those requirements at selected waste sites. What makes the experience to date incomplete is the lack of regulatory requirements and technical experience dealing with deep vadose zone plumes.

In a wetter environment with a shallower water table, the existing technical requirements are typically reasonable, appropriate, and sufficient, especially given that the contaminants can always be retrieved for treatment and disposal. In the dry environment at the Hanford Site, with its thick vadose zone and deep groundwater, the requirements may not be sufficient. For example, contaminant plumes in the thick vadose zone may be costly and time-consuming to detect and quantify. Surface barriers are most protective of the contaminants located just beneath the cover; for contaminants located deep in the vadose zone, the level of protection is less defined. It may take decades to centuries for contaminants to reach the groundwater, which means that the lack of detection in the early years might create a false sense of adequate protection.

The current monitoring approach for closure and post-closure conditions is to monitor the surface barrier (and leachate sump, if one exists) to detect potential or imminent entry of water into the contaminated zone and to monitor the groundwater downgradient of the site to detect contaminants leaving the contaminated zone. This approach is not timely for sites with a thick vadose zone, but to date there is no promulgated regulatory requirement, no body of experience using vadose zone monitoring (other than to support surface barrier evaluations), and no consensus on a set of monitoring technologies appropriate to the deep vadose zone. Quadrel and Lundgren (2000, p. 589) noted that the lack of firm and predictable regulatory requirements for vadose zone remediation results from an "insufficient scientific and technical basis for promulgating guidance or readily supporting case-by-case corrective actions."

4.2 Field Observations

Since the 1970s, field observations of subsurface water and contaminants have been conducted at a number of sites at Hanford and for a number of purposes. Those observations provide estimates of recharge for specific surface barrier designs and soil types. They also provide estimates of contaminant transport for specific contaminants at specific sites. Summarized below is a selection of field-oriented data collection efforts to be considered when developing activities to support the barrier evaluation strategy.

4.2.1 Prototype Hanford Barrier

The Prototype Hanford Barrier (PHB) is a multilayer barrier that was designed to reduce infiltration, resist erosion, prevent plant and animal intrusion, and last at least 1000 years. The PHB started operation in 1994 over the B-57 crib as part of a treatability study (DOE-RL 1999); the location is the northern 200 East Area, adjacent to the BY tank farm and the BY cribs. The PHB also has two different side slope designs, which is unique, and differences in their response highlight the need for a design standard. The barrier and side slopes are instrumented and monitored to provide long-term performance data. Ward et al. (2007) summarized the data collected through September 2007, which means the length of record is nearly 13 years.

Key observations include the following:

- *Infiltration through the barrier was well below 0.1 mm/yr.* Over the 13-year period, combined drainage from the soil-covered plots was only 0.45 mm (0.03 mm/yr). This very low rate is significant, given that there were several reasons for the rate to be much higher. First, the period of record included 2 years (1995 and 1996) with record amounts of precipitation (313 and 310 mm/yr, respectively). Second, during the first 3 years of testing, half the barrier was irrigated such that the total water received was equivalent to an annual precipitation of about 480 mm/yr, which is nearly three times the current average annual precipitation rate of 172 mm/yr. Finally, the plant community took several years to become fully established.
- *Infiltration through the side slopes was sometimes significant.* In the first 4 years, when 2 years had record precipitation and before vegetation became established, the south gravel side slope drained 70.0 mm/yr. In the subsequent 9 years when plants had become established, the south gravel side slope drained 13.4 mm/yr. In contrast, drainage through the south basalt side slope during the same two periods was 50.3 and 11.5 mm/yr, respectively. Furthermore, during the same 9-yr period, drainage through the north gravel side slope was 22.6 mm/yr; through the north basalt side slope, it was 15.8 mm/yr. The differences between side slopes of the same design indicate the degree of variability to be expected. The differences between side slope designs indicate the need for a design standard. The basalt side slope had a similar response, even though there are no plants growing on this side slope.
- *Lateral flow directly beneath the barrier is limited.* Below the barrier, water contents are monitored with a neutron probe that is passed through a set of horizontal access tubes located 1, 2, and 3 m below the asphalt. To date, water content has not increased beneath the asphalt except within 1–2 m of the edge of the asphalt, where it increases and decreases seasonally in response to drainage beyond the asphalt layer.

- *Some characterization data exist for the deep vadose zone.* Prior to barrier construction, the site was initially characterized with boreholes to the water table and was part of a recent geophysical investigation of the BY-BX tank complex.
- *No deep vadose zone monitoring occurs at this site.*

4.2.2 Field Lysimeter Test Facility

The Field Lysimeter Test Facility (FLTF) is a set of lysimeters with various soil and plant combinations that provide water balance data to help design surface barriers and estimate recharge rates. The FLTF is adjacent to the Hanford Meteorological Station, which is just outside the northeastern corner of the 200 West Area. Some of the existing lysimeter tests date back to the FLTF starting date of November 1987, which means the length of record is 22 years. Nichols et al. (2008) provided the most recent summary of the data.

Key observations include the following:

- *Hanford Barrier designs limit deep drainage to much less than 0.1 mm/yr.* This result occurred for the following conditions:
  - 1.0-m-thick silt loam layer above a capillary break; shrub-steppe vegetation; ambient precipitation and enhanced precipitation (i.e., 3 times normal)
  - 1.5-m-thick silt loam layer above a capillary break; shrub-steppe vegetation; ambient precipitation and enhanced precipitation (i.e., 3 times normal)
  - 1.5-m-thick silt loam layer above a capillary break; no vegetation; ambient precipitation; 22-year record
  - 2.0-m-thick silt loam layer above a capillary break; shrub-steppe vegetation; ambient precipitation and enhanced precipitation (i.e., 3 times normal).
- *Deep drainage beneath sands and gravels with little to no vegetation was significant.* Dune sand drainage was 40 mm/yr; sandy gravel drainage was 98 mm/yr; gravel mulch drainage was 89 mm/yr; and pit-run sand drainage was 25.1 mm/yr.
- *No deep vadose zone monitoring occurred at this site.*

4.2.3 300 North Lysimeter

The 300 North Lysimeter refers to a single 7.6-m-deep lysimeter in a set of lysimeters once known as the Buried Waste Test Facility. The lysimeter is located midway between the 300 and 400 Areas. The lysimeter is filled with sand excavated to construct the facility. The sand is coarse, and most of the gravel was removed. Other than occasional small annuals, no vegetation has been allowed (or even attempted) to grow on the lysimeters. Data collection began late in 1978. Nichols et al. (2008) provided the most recent summary of the data.

Key observations include the following:

- *Water content changes were dampened with depth.* The impact of individual precipitation events is readily apparent at the 30-cm depth and barely perceptible at the 90-cm depth except during winter months following multiple precipitation events.
- *Matric potential changes were dampened with depth.* The impact of individual precipitation events was apparent at the 90-cm depth (the shallowest sensor). At deeper depths, the response was muted and seasonal.
- *Deep drainage was significant.* The deep drainage rate was 62.1 mm/yr from 1981 to July 2008, which is a 27-year length of record. There was no attempt to promote vegetation growth and, beyond an occasional sprinkling of annuals, plants did not establish naturally, likely because of the poor nutrient and physical properties of the sand.
- *No deep vadose zone monitoring occurred at this site.*

4.2.4 Solid Waste Landfill Lysimeter

The Solid Waste Landfill Lysimeter is an 85-m^2 basin lysimeter without sidewalls constructed under one of the landfill cells of the Solid Waste Landfill, which is located off the Central Plateau about 6 km southeast of the 200 East Area. The lysimeter began operating in 1992; measurable drainage first appeared in July 1996.

Nichols et al (2008) provided the most recent summary of the data. Key observations include the following:

- *Surface soil has coarse texture.* The surface soil is mostly coarse sand to fine gravel, which maximizes infiltration, minimizes bare surface evaporation, and provides minimal support for plant growth.
- *Vegetation is sparse.* In 2008, plant cover was only 24% and leaf area index was only 0.02.
- *Deep drainage was significant.* The drainage rate was 48.1 mm/yr from July 1996 to June 2008, a 12-year length of record.
- *No deep vadose zone monitoring.* Other than the collection of drainage by the basin lysimeters, there is no vadose zone monitoring at this site.

4.2.5 T Farm Interim Surface Barrier

The T Farm Interim Surface Barrier is a temporary barrier placed over a portion of the T Farm to reduce infiltration directly above the vadose zone contaminant plume created by the major leak from subsurface tank T-106 in 1973. The barrier was completed in April 2008; it is composed of an impermeable 1/4-in.-thick layer of polyurea that is sloped to collection troughs that route the precipitation water to an infiltration pond located just outside the north fence of T Farm. Temperature, water content, and matric potential are measured at four locations—two under the barrier, one under the edge, and one 10 m away from the outer edge of the barrier. Sensor depths vary between 0.6 and 10 m. Additionally, water contents are measured with a neutron probe to as deep as 15.24 m. Zhang et al. (2009) provide details of the measurements conducted in fiscal year 2008. The results include a full year of data for the sensors outside the barrier, but only 5 months for the sensors beneath the barrier.

Key observations include the following:

- *Temperature changes were dampened with depth.* The largest temperature changes occurred closest to the soil surface. At progressively deeper depths, the temperature changes were increasingly damped and peaks were shifted in time. For example, at the 1-m depth outside the barrier, temperature varied between 3°C and 29°C and the peak was in August. In contrast, at the 10-m depth, temperature varied between 17°C and 18°C and the peak was in March.
- *Matric potential changes were dampened with depth.* The largest matric potential changes occurred closest to the soil surface. At progressively deeper depths, the matric potential changes were increasingly damped and peaks were shifted in time. For example, at the 1-m depth outside the barrier, matric potential varied between −3.5 and 0 m and the peak occurred in February through March. At the 10-m depth, matric potential varied between −1.5 and −1.3 m and had no discernible peak.
- *Influence of the barrier detected within 5 months.* Zhang et al. (2009) report that the barrier is beginning to have an effect on water contents in the 0- to 2-m depth range.
- *No deep vadose zone monitoring below 50 ft.*

4.2.6 Tank Farms

The current body of tank-farm-related knowledge useful for tank farm risk assessments is described in a RCRA Facility Investigation (RFI) report (DOE-ORP 2008). The RFI report integrates the results of data-gathering activities and evaluations for all Hanford Site single-shell tank (SST) waste management areas (WMAs) with conclusions and recommendations, documents field investigations at the A, AX, C, and U tank farms (some are discussed in Section 4.3.2), provides data collected at the B-BX-BY, S-SX, T, and TX-TY tank farms, and provides all available information for the SST farms that support retrieval and closure.

The field activities that provide data include boreholes, direct push tests, and geophysical measurements. Boreholes provided soil samples for laboratory testing and analysis, access for geophysical tools (e.g., spectral gamma sonde, neutron sonde,), and placement for a variety of monitoring sensors. In all, the Tank Farm Vadose Zone Program drilled a total of 11 boreholes to depths ranging from 127 to 264 ft. Measurements made within the boreholes include gamma-emitting radionuclides and water content. The gamma data provided both gross gamma, which sums all gamma energy, and spectral gamma, which was used to identify and quantify specific radionuclides. The boreholes were used also to insert sensors such as soil water probes, water potential probes, suction lysimeters (for extracting pore water samples), and electrodes for resistivity measurements.

Direct push tests provided subsurface access similar to normal boreholes. Sediment samples were collected for analysis, and sondes were used to make gamma and water content measurements. The maximum depth of penetration is limited to about the upper 100 ft because of difficulty of pushing through the vadose zone.

Geophysical tests conducted in the tank farms included ground-penetrating radar, electromagnetic induction, differential magnetometry, and electrical resistivity. Outside the tank farms, geophysical tests using seismic, cross-borehole radar and seismic, and induced potential techniques have provided data that could supplement the within-farm data.

In the early days at the Hanford Site, gross gamma logging of boreholes provided a means of detecting releases from the single-shell tanks. In addition to the normally vertical boreholes, two of the tank farms have tanks with lateral boreholes located directly beneath the tanks. Measurements in both vertical and horizontal boreholes were conducted on a routine schedule that ranged from weekly to annually. More recently, the emphasis of gamma logging has been on monitoring the stability of radiological plumes present in the vadose zone. DOE-ORP (2008) provides multiple examples in which spectral gamma data were used to characterize transient plume behavior.

DOE-ORP (2008) summarized the recommendations of multiple tank-farm–related studies and of an initial SST performance assessment study. Key recommendations by previous studies and reiterated by DOE-ORP (2008) include the following:

- *Improve estimates of past release inventories* lost to the vadose zone.
- *Use site-specific data* to model each WMA.
- *Estimate impacts from surrounding facilities* on impacts from WMAs.

One final observation is that the preponderance of characterization in tank farms has been around and just beneath the tanks.

4.2.7 BC Cribs and Trenches

Eslinger et al. (2006) identified BC cribs and trenches as a site with potentially significant deep vadose zone contamination. Ongoing projects are examining aspects of the remediation investigation. One of those projects is developing the means to use geophysical techniques and sediment sampling to characterize the three-dimensional distribution of contaminants, notably nitrate and technetium-99. Serne et al. (2009) reported that electrical resistivity information derived using surface electrodes was able to define the lateral extent of the plume with concentrations greater than 0.3 M. Serne et al. also report that the lower leading edge of the observable plume was 130, 160, and 260 ft below ground surface in the three boreholes from which sediments were obtained for analyses. The local groundwater level is at about 340 ft below ground surface, which supports the theory that contaminants from the BC cribs have not yet reached the groundwater and therefore represent a continuing deep vadose zone challenge.

Key observations include the following:

- *Need deeper electrodes* to improve characterization and monitoring of the deep vadose zone.
- *Need improved laboratory-field correlations* of physical, and geochemical, and resistivity properties.
- *Need better models and computers* for three-dimensional inversions of resistivity data and geochemical analyses.

Serne et al. (2009, p. 10.6) noted "...there is no other region at Hanford that has such a comprehensive data base of characterized sediments; so BC Cribs and Trenches is the best available "groundtruthing" test bed for all types of ERC [electrical resistivity characterization] field survey techniques."

4.3 Modeling Studies

Modeling is a tool that enables analysis and prediction of processes that are difficult or impossible to measure (e.g., contaminant transport in the deep vadose zone). Models are the only tool available for predicting what may happen in the future. Therefore, in the context of planning and executing Hanford cleanup, models are essential, which explains why a significant number of modeling studies have been conducted at Hanford. Summarized below is a subset of those modeling studies to provide context to the discussion of modeling in the barrier evaluation strategy.

4.3.1 Hanford Defense Waste Environmental Impact Statement

The Hanford Defense Waste Environmental Impact Statement (HDW-EIS; DOE 1987) identified the need for surface barriers to protect groundwater from subsurface contaminants for at least 10,000 years. Appendix M of the HDW-EIS described the surface barrier design under consideration at that time and presented analyses of its performance for specific soil and vegetation conditions. Figure M.3 shows a cross section of the barrier that includes the side slope and a buried tank. Although Figure M.3 indicates the functional edge of the barrier should be 10 to 30 m beyond the edge of the tank, there is no discussion of edge effects in Appendix M to support the choice of that distance. Appendix M also summarizes a research program that was active at that time called the Protective Barrier and Warning Marker System (Adams and Wing 1987); that program eventually evolved into the Barrier Development Program mentioned in Section 2.2 (Wing 1994).

Concurrent with preparation of the HDW-EIS, the Barrier Development Program was researching various issues related to surface barriers. One of those issues was the edge effect. Using numerical modeling, Fayer (1987) showed that subsurface hydraulic properties have a significant effect on the flux of water moving past the waste zone when it was located 10 m from the functional edge of the barrier. Fluxes were lowest for the coarsest sediments and highest for the finer-textured sediments. In one simulation, lateral flow caused by a single fine-textured layer outside the barrier did not appreciably increase flux past the waste when the sediments around the waste zone were coarse-textured.

4.3.2 Tank Farm Evaluations of Surface Barriers

One of the concerns regarding the SST WMAs is their long-term risks to groundwater. Two types of investigations were conducted in which the impact to groundwater from surface barrier emplacement was evaluated. One type was Closure Assessments (CAs), which were focused on contaminant leaks related to future tank closure activities. The second type was Field Investigation Reports (FIRs), which were focused on tank leaks that have already occurred. Numerical simulations of flow and solute transport for the CAs (e.g., Freedman et al. 2005; Zhang et al. 2005) and FIRs (e.g., Freedman et al. 2002; Zhang et al. 2004) investigated the impact of variable recharge rates on groundwater by comparing peak concentrations and arrival times in a hypothetical groundwater monitoring well located at a downstream compliance point.

In general, the approach for assigning recharge rates was similar for the two types of investigations. Contaminant transport was simulated for the years 2000 to 12000. Initially, the tank farm surfaces were graveled and maintained free of vegetation, so the pre-closure recharge rate was set to 100 mm/yr based on the recommendations of Gee et al. (1992) for the soil and vegetation conditions of tank farms. The pre-closure recharge rate was applied from 2000 to 2032. In the year 2032, the recharge rate was reduced to 0.5 mm/yr to represent placement of the closure barrier. For the next 500 years, the closure barrier was assumed to be operating at maximum efficiency. In the year 2532, the recharge rate was increased to 1.0 mm/yr to represent potential degradation of the closure barrier. Site-specific groundwater gradients were used for each of the assessments, but the thickness of the groundwater table was the same for each of the assessments to facilitate comparisons.

A major difference between the CA and FIR simulations was that the FIR included an examination of the impact of an interim barrier placed around 2010. The recharge rate of the interim barrier was 0.5 mm/yr. The interim barrier was assumed to be functional until placement of the closure barrier in about 2032. The reduction in recharge between 2010 and 2032 led to longer travel times for contaminants in the vadose zone and smaller peak concentrations at downstream compliance points. Although lower peak concentrations resulted, concentrations on the falling limb of the breakthrough curves (i.e., after the peak had occurred) were higher.

Although they did not evaluate interim barrier impacts, the CAs examined the sensitivity of the peak concentrations and arrival times to a range of estimates for the pre-closure, barrier, and degraded barrier recharge rates. In general, each of the contaminant release scenarios responded similarly to changes in recharge rates. Differences in responses were due primarily to the contaminant release rate and the position of the contaminant in the soil profile. For example, increasing the pre-closure recharge rate [median = 100 mm/yr, lower bound = 4 mm/yr, upper bound = 140 mm/yr] increased peak concentrations and accelerated the arrival times of the peaks, whereas the reverse trend occurred when the pre-closure recharge rate was decreased. The extent of the impact was most significant for contaminant distributions located close to the water table. Because the pre-closure recharge rate was used for a short period (~32 years) relative to the entire simulation, the impact on contaminants positioned closer to the ground surface was smaller because their peaks occurred much later in the simulations.

In general, variations in the closure barrier recharge rate [median = 0.5 mm/yr, lower bound = 0.1 mm/yr, upper bound = 1.0 mm/yr] had a relatively small impact on changes in peak concentrations and arrival times. However, the degraded barrier recharge rate [median = 1.0 mm/yr, lower bound = 0.5 mm/yr, upper bound = 3.5 mm/yr] had its largest impact when contaminant releases occurred by diffusion and contaminants were still being released into the subsurface when the degraded barrier recharge rate became effective. Larger changes in peak concentrations and arrival times occurred with the more retarded species because more of the mass remained in the domain once the degraded barrier recharge rate became effective. For other contaminant release scenarios, the contaminants were released more quickly and the degraded barrier recharge rate had a minimal impact on results.

In summary, the CAs and FIRs confirmed the sensitivity of groundwater to recharge rates in the pre-barrier, barrier, and post-barrier periods. As recharge rates were reduced, peak concentrations in groundwater were reduced and delayed. Neither the CAs nor the FIRs examined a "no-barrier" scenario. Issues that were not addressed include heterogeneity and anisotropy in the vadose zone, variations in the aquifer thickness and groundwater flow rate, and barrier side slope effects.

4.3.3 Ward (2004)

Ward et al. (2004) used numerical simulations to illustrate the effects of heterogeneity on subsurface contaminant distributions and to evaluate the value of a surface barrier at the BC cribs. A number of waste trenches and cribs at Hanford's BC cribs and trenches site, which received about 10 million gal of scavenged tank waste with elevated concentrations of technetium-99 and nitrate, are being evaluated for remediation. Toward the goal of developing an appropriate remedial strategy, the objectives of this study were 1) to develop a conceptual model for vadose zone transport of mobile contaminants and 2) to investigate the effects of fine-scale heterogeneity (i.e., horizontal laminations, cross-bedding) on the large-scale transport behavior. The vertical heterogeneity structure, conditioned on grain- size distributions and borehole geophysical logs (water content and natural isotopes), was developed from a single borehole at the site. Geostatistical methods were used to impose a three-dimensional spatial correlation structure, using information from the adjacent well-characterized Sisson and Lu site, as well as to merge heterogeneities at various scales. Flow and transport properties were derived using property-transfer models based on grain-size distributions. The STOMP simulator was used to predict flow and transport through the vadose zone and into a 5-m-thick unconfined aquifer during the period of trench operations (1956–1958) up to the present time.

Figure 4.1 shows the predicted distribution of ^{99}Tc at the beginning of 2005. In general, the predicted plume is located between 20 and 50 m below ground surface. The current conceptual model suggests that the discharges from the seven trenches initially moved laterally to merge into a single plume. Natural recharge then leached the trailing edge of the plume downward, effectively reducing the concentration of the mobile contaminants in the 0- to 20-m depth to background levels. The plume shows some effects of the heterogeneity in that it is asymmetric and multimodal. Under Trench 216-B-26 where the C4191 borehole was installed (northing = 110 m), the plume is located between 23 and 50 m below ground surface. Figure 4.1 shows an overlay of the electrical resistivity contours derived from a surface resistivity survey conducted at the site in 2003. The distribution of resistivity, a reflection of the distribution of ionic solutes, is in good agreement with the distribution of nitrate. Because of the similarity in the transport behavior of ^{99}Tc and NO_3^-, the electrical resistivity profile is also correlated with ^{99}Tc. However, it should be noted that in the absence of the high nitrate concentrations, it is unlikely that a resistivity survey would have been able to delineate the plume.

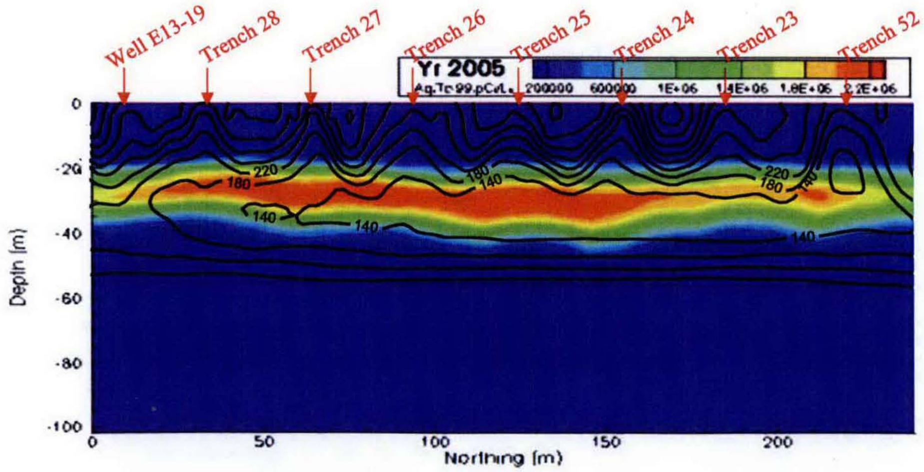


Figure 4.1. Calculated Distributions of Aqueous ^{99}Tc in the Year 2005 and Electrical Resistivity Contours from a Surface Resistivity Survey Conducted in 2003 (adapted from Ward et al. 2004, p. 5.26, Figure 5.24)

In the absence of multidimensional plume distribution data, comparisons between the simulated and observed ^{99}Tc distribution are based on data from the C4191 borehole. To make this comparison, Ward et al. (2004) extracted a one-dimensional profile beneath the 216-B-26 trench at the approximate location of the C4191 borehole. Figure 4.2 compares the predicted depth profiles for NO_3^- and ^{99}Tc with the profiles measured at the location of borehole C4191. The general trends are remarkably similar, given the uncertainty in hydrologic properties and the lack of hydrologic characterization data. The predicted distributions of NO_3^- and ^{99}Tc are remarkably similar to the field observations. In both cases, the predicted center of mass is very similar.

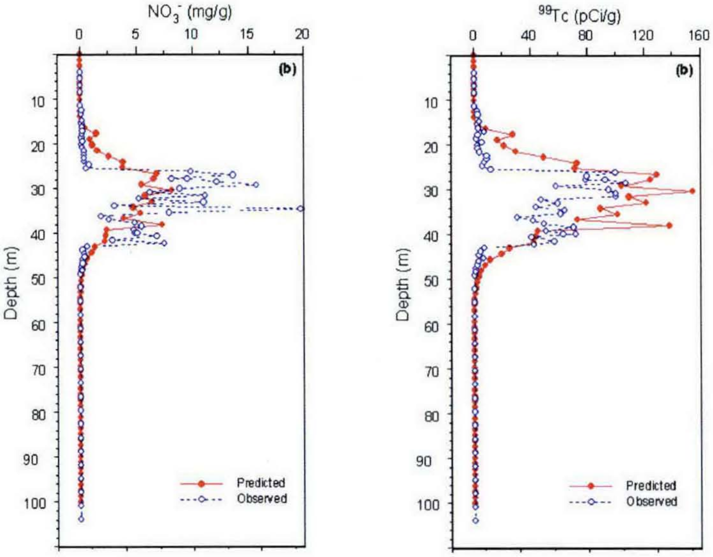


Figure 4.2. Observed and Predicted Distributions of Mobile Contaminants at Borehole C4191 in 2005. (a) Aqueous NO_3^-, and (b) ^{99}Tc (adapted from Ward et al. 2004, p. 5.28, Figure 5.26, and p. 5.30, Figure 5.27)

The center of mass of the predicted ^{99}Tc and NO_3^- plumes is located around 30 m, and the leading edge of the plume extends to around 50 m, as in the case of the measured plume. The plots in Figure 4.2 show the effects of small-scale heterogeneities on the contaminant profiles, which is a reflection of depth variations in water content and bulk density.

In general, these results show that fine-scale heterogeneity within the large-scale lithologic units enhanced lateral flow and mixing, limited vertical penetration in the vadose zone, and played a critical role in keeping contaminants above the water table. Model results show good agreement with a contaminant profile from a borehole installed in the 216-B-26 trench. Although the model captured the leading edge of the plumes well, the trailing edge appears to have been insufficiently leached, thereby giving an apparently larger value of dispersion. First, the model appears to underestimate the concentration of NO_3^- whereas it slightly overestimates the concentration of ^{99}Tc. For nitrate, the predicted peak concentrations based on the input inventory are about one-third those of the observed. Given that the transport behavior of ^{99}Tc and NO_3^- are expected to be similar, the amount of dispersion in an advection-dominated environment would be expected to be similar. Simulated distributions of nitrate and electrical resistivity are also in good agreement with the results of a field-scale resistivity survey. These results suggest that the installation of an engineered surface barrier would reduce the threat to groundwater by increasing the residence time in the vadose zone and reducing the mass flux of contaminants to the water table.

4.3.4 Eslinger et al. (2006)

In 1998, DOE sought the ability to conduct large-scale environmental assessments of the Hanford Site. With DOE direction, the Groundwater Vadose Zone Integration Project initiated development of the System Assessment Capability (SAC), a suite of interrelated computer codes designed to meet DOE's environmental assessment needs at the Hanford Site (Eslinger et al. 2006). Developed by Pacific Northwest National Laboratory, the SAC models the fate and transport of radioactive and chemical contaminants in the environment and the associated human and ecological impacts. The SAC addresses the source term, waste release, vadose zone, groundwater, air, and the Columbia River, and it supports both deterministic and stochastic analyses.

Eslinger et al. (2006) used the SAC to conduct a study to rank the risk from Central Plateau waste sites. For inventory, they considered liquid discharges, solid waste burials, and unplanned releases, as well as some other releases. Their study did not address the residuals in the SSTs or double-shell tanks. For all waste sites identified to receive a surface barrier, a barrier was assumed to be emplaced and have a recharge rate of 0.5 mm/yr for 500 years and 1.0 mm/yr thereafter. Barrier side slope and edge effects were not considered. The SAC models are capable of multidimensional simulations, but for reasons particular to this study, the vadose zone calculations were conducted in one dimension in which the size of the wetted area was scaled based on maximum liquid discharge rates and minimum saturated hydraulic conductivity of the vadose zone lithologies. Because all vadose simulations were conducted in one-dimension, lateral flow induced by heterogeneities in sediment properties and geologic lithologies was not addressed.

The results were presented relative to three metrics—the drinking water standard, the risk of exceeding the all-pathways dose standard for a residential farmer (based on ^{99}Tc, ^{129}I, and $^{234/238}$U), and the risk of exceeding 10 times the drinking water standard or the dose standard. Individual sites were grouped into larger units for parsimony. At least seven of the group sites had peak groundwater concentrations of ^{99}Tc that exceeded the drinking water standard of 900 pCi/L. Eleven of the group sites exceeded the peak residential farmer dose of 15 mrem (and eight other sites were close). Eight of the group sites exceeded 10 times the drinking water standard. Some of the metrics were exceeded well in the future, suggesting that the plumes resided in the vadose zone for a very long time before reaching the groundwater. The findings of the study by Eslinger and colleagues were used, in part, to identify sites with the potential to have significant deep vadose zone contamination (DOE-RL 2008).

Key findings for this report include the following:

- *Multiple sites* have potential for significant quantities of contaminants in the deep vadose zone.
- *Surface barrier evaluation* was for screening purposes only. Of necessity, the analysis did not address barrier edge effects or lateral flow.
- *Report provides the basis for the treatability plan* identification of potential deep vadose zone sites.

4.3.5 DOE/RL-2007-35

DOE-RL (2007) used numerical simulations to establish remedial action goals (RAGs) for maximum soil contamination levels that are still protective of groundwater beneath the 200-UW-1 Operable Unit. Although the purpose was to establish soil cleanup levels in the shallow vadose zone (0 to 15 ft below ground surface), the RAGs methodology could be used to inform surface barrier design and deep vadose zone characterization and monitoring.[1]

For its RAGs study of the shallow vadose zone, DOE-RL (2007) identified the appropriate groundwater protection metric to be the maximum contaminant level (MCL) for each contaminant. The MCL is the highest level of a contaminant that is allowed in drinking water. The STOMP computer code was used to simulate the transport of contaminants from the shallow vadose zone to a groundwater monitoring well located 100 m downgradient of the site. The predicted concentration in the well was divided by the MCL to create a scaling factor that was used to estimate the maximum soil concentration that could exist in the shallow vadose zone that would not result in a peak concentration at the well that exceeded the MCL.

The analysis examined the sensitivity of the results to variations in many parameters, including instantaneous equilibrium distribution coefficient (K_d), recharge, hydraulic conductivity, source term depth and thickness, dispersivity, anisotropy, and residual moisture. The analysis also examined the sensitivity of the results to numerical conditions such as grid size and Courant control of the time step. Of all the parameters and conditions evaluated, recharge and K_d variations had the greatest impact on groundwater concentrations. The analysis did not address the impact of placing a surface barrier.

4.3.6 Bauer (2007)

Bauer (2007) conducted a design analysis for an interim surface barrier to protect groundwater from vadose zone contaminants released during a 1973 leak from tank 241-T-106 in T Farm. Because the barrier design used an impervious foam urea, Section 1 of the analysis addressed runoff and its conveyance to an infiltration zone north of T Farm. Infiltration zone capacity was sized to hold the 8,122 ft^3 of runoff that would result from a 25-year 24-hour storm. The infiltration zone was designed with an overflow outlet to prevent stormwater in excess of the design storm from backing up onto the cover. Section 8 of the analysis[2] examined the impact of the barrier on future concentrations of nitrate, chromium, uranium, and ^{99}Tc in groundwater. For that analysis, the STOMP code was used to conduct two-dimensional simulations to examine the effect of surface barrier size during 1000 years following barrier placement. To highlight the impact of a barrier, predicted groundwater concentrations in the presence of a barrier were divided by the concentrations predicted without an interim barrier. Sensitivity cases were conducted to examine the influence of the buried tank, runoff disposal, a less-than-impermeable interim barrier, and various depths of contamination.

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[1] The methodology for deriving vadose zone contaminant levels protective of groundwater was discussed with DOE-RL in late 2006 (Hoover JD and WJ McMahon, "Determination Remedial Action Goals (RAGs) for Soil Levels Protective of Groundwater at 200-UW-1 Using Alternative Fate and Transport Modeling," Presentation to DOE-RL on 27 October 2006). The CHPRC plans to publish this "RAGs" methodology for deep vadose zone contamination in 2010.

[2] Section 8 was authored by Bill McMahon, CH2M HILL Plateau Remediation Company.

Key findings include the following:

- *Interim barrier size effect* was to reduce peak groundwater concentrations by 40% to 60% for a barrier the size of the plume. For a barrier twice the size of the plume, the reduction was 53% to 74%.
- *Runoff control* was significant. When runoff was allowed to infiltrate at the edge of the interim barrier, the barrier reduced peak concentrations by only 10%. When runoff was allowed to infiltrate 70 m from the barrier, the results were nearly identical to those with no runoff.
- *Leaky interim barrier* that allowed 10 mm/yr recharge yielded no significant difference from an impermeable barrier.
- *Contaminant depth* impacted the barrier effect. For unretarded contaminants at 20 m, the barrier reduced peak concentrations by 87%. For unretarded contaminants at depths ranging from14 to 40 m (the actual distribution observed in the vicinity of T-106, the barrier reduced peak concentrations 40% to 50%. For unretarded contaminants at or below 50 m, the results showed very little amelioration of peak groundwater concentrations by placement of an interim barrier.
- *Vadose zone impacts* were observable outside the lateral extent of the barrier. As water drained from the vadose zone beneath the interim barrier, a lateral hydraulic gradient was established that caused a reduction in water contents in the vadose zone outside the barrier extent. The decrease was not as large as observed directly under the barrier.

4.3.7 Piepho and Benecke (2007)

Piepho and Benecke (2007) used numerical simulations to evaluate the ability of a surface barrier to protect groundwater from vadose zone contaminants. In the conceptual model, the vadose zone consisted of a single isotropic material with no layering, the contaminated zone was 3 m high and 120 m wide, the surface barrier had a recharge rate of 0.5 mm/yr, water contents in the contaminated zone were higher (0.04 vol/vol) than the surrounding vadose zone, and the depth to groundwater for most cases was 104 m. The authors considered several variables in the study, including two initial recharge rates (5 and 25 mm/yr), contaminated zone depths ranging from 30 to 100 m, and surface barrier extent beyond the contaminated zone ranging from 15 m to infinity.

Piepho and Benecke (2007) established two metrics for the evaluation of barrier effectiveness: 1) time delay factor (TDF) and 2) concentration reduction factor (CRF). Both were evaluated at a well 100 m downgradient from the edge of the contaminated zone. The TDF is the ratio of the time for the peak concentration to occur when a barrier is in place to the time for the peak to occur when a barrier is not in place. The CRF is the ratio of the peak concentration when a barrier is in place to the peak concentration when a barrier is not in place. These factors are relative and do not address acceptability for a specific site.

The results showed that, for the case with an initial recharge 25 mm/yr, placement of a surface barrier increased the TDF by a factor of 20. The CRF was 28 for contaminants located at the 30-m depth and decreased to nearly 1.0 for contaminants at the 100-m depth. For the case with an initial recharge rate of 5 mm/yr, the TDF and CRF values were 6 and 7, respectively, at the 30-m depth; both decreased to nearly 1.0 at the 100-m depth. The results from both cases suggest that a surface barrier significantly protects groundwater from contaminants that are at the 30-m depth and provides very little protection when contaminants are located at the 100-m depth (i.e., 4 m above the groundwater surface).

Piepho and Benecke (2007) examined the distance between the edge of the barrier and the contaminated zone and also considered the impact of an anisotropy factor of 10. The simulation results for an overhang of 0.0 m and contaminants at the 30-m depth yielded a peak groundwater concentration that was about one-half the concentration under an infinite barrier. This result suggests that water flowing under the barrier edge diluted the contaminant concentration in the groundwater. When contaminants were located at deeper depths or when barriers had greater overhang distances, the resulting groundwater concentrations approached the value observed for an infinite barrier. In two cases involving contaminants at depths of 50 and 70 m, an overhang of 0.0 m resulted in peak groundwater concentrations that were about 25% higher than those under an infinite barrier. When anisotropy was included, the peak groundwater concentrations increased for some cases. For example, for the case with contaminants at the 50-m depth and an overhang of 15 m, the peak groundwater concentration was 2.79 times greater than the peak under an infinite barrier. For the similar isotropic case, the peak groundwater concentration was about 0.9 times the peak under an infinite barrier.

The Piepho and Benecke (2007) results suggest the following:

- *Contaminant depth*: The deeper the zone of contamination is, the less effective a surface barrier can be.
- *Initial recharge*: The higher the initial recharge is, the more effective a barrier can be.
- *Barrier overhang distance*: The results from using an overhang distance of 60 m resembled those of the infinite overhang case. Shorter distances (down to 15 m) had only minimal impact on the performance metrics. The large lateral size of the contaminated zone and the use of a single isotropic geologic medium may have reduced the potential for impact from short overhang distances.
- *Anisotropy*: For cases examined, increasing the lateral conductivity by a factor of 10 had minimal impact on the contaminant concentrations in groundwater at the well.

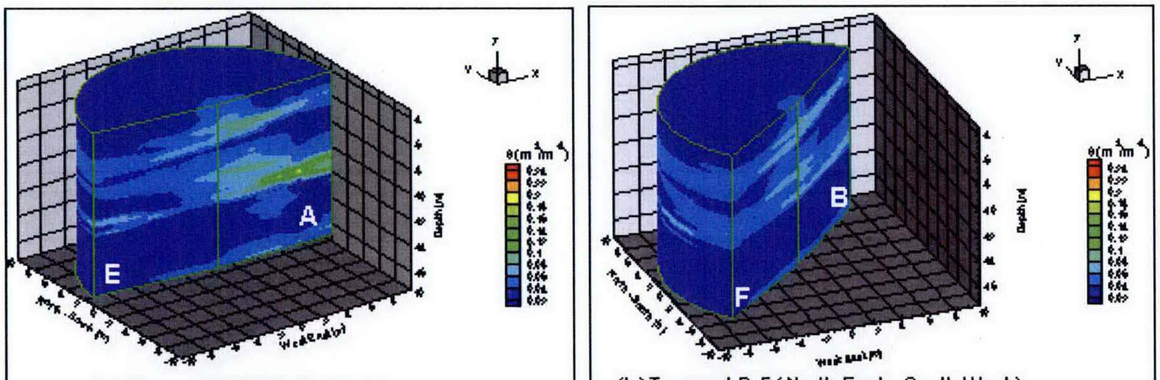
Issues that were not addressed by Piepho and Benecke (2007) include the areal size of the waste zone, anisotropy and heterogeneity of the vadose zone, surface barrier recharge rates other than 0.5 mm/yr, variations in the aquifer thickness and groundwater flow rate, three dimensional effects, barrier side slope effects, and variations in recharge in areas not covered by the surface barrier.

4.4 Vadose Zone Transport Studies

Observations at several of Hanford's waste sites suggest that vadose zone transport is controlled by a complex interplay between recharge, layered heterogeneity, geometric anisotropy, and saturation-dependent anisotropy. Phenomena like saturation-dependent anisotropy become particularly important in the deep vadose zone where antecedent soil water content is generally low. A number of studies have been conducted to improve the understanding of these processes; one of the earliest was the Sisson and Lu (1981) injection experiment. Summarized below are two recent science-oriented studies. The first describes an experiment conducted at the site of the original Sisson and Lu experiment in the 200 East Area. The second describes a DOE Office of Science study of the impact of clastic dikes on vadose zone flow and transport.

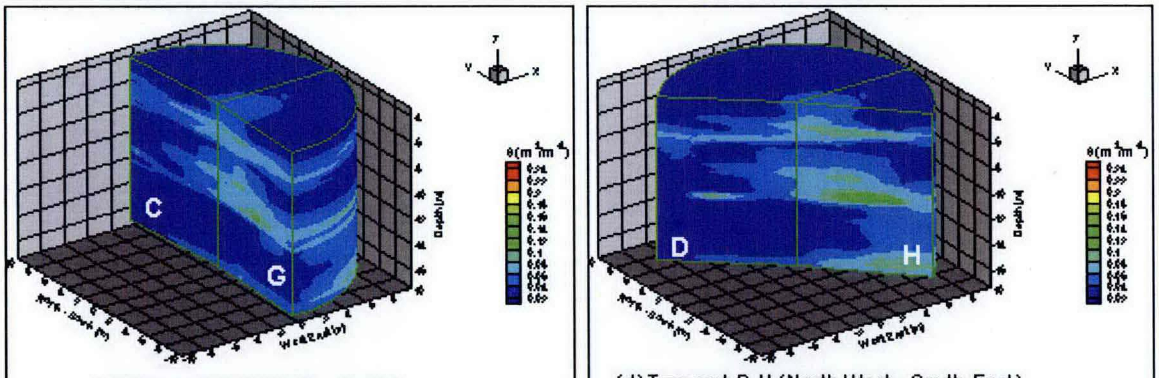
4.4.1 Science and Technology Testing at Sisson and Lu Site

As part of a Science and Technology Project, a series of studies was conducted at the Sisson and Lu site over a 2-yr period to investigate the impacts of layered heterogeneity and anisotropy on field-scale transport and to determine whether fluid properties associated with hypersalinity had any effect on transport behavior in the deep subsurface (Ward et al. 2006b). The flow field, which was monitored using a variety of geophysical tools (neutron thermalization, electrical resistivity/conductivity, and ground penetrating radar) and destructive sampling, showed significant asymmetry resulting from fine-scale stratigraphic changes (Figure 4.3). Part of the complexity arises from the presence of low-permeability layers and natural capillary breaks (i.e., fine-textured layers underlain by coarser sediments). During variably saturated flow, these structures can cause fluids to flow laterally. In the case of capillary breaks, the enhancement of lateral flow diminishes as the matric potential increases (i.e., the sediment becomes wetter). Figure 4.3 shows the moisture distributions after the injection of 30,400 L of water. The effect of local capillary breaks is evident in the nonuniform distribution of moisture. A low-permeability layer at the 12-m depth was effective in stopping the downward migration of water except in the southeastern corner (Figure 4.3d) where water bypassed this layer, perhaps via a borehole. The fine-scale layering



(a) Transect A-E (East - West)

(b) Transect B-F (North East - South West)



(c) Transect C-G (North - South)

(d) Transect D-H (North West - South East)

Figure 4.3. Spatial Distribution of Soil Water Content, θ, Interpolated from Neutron Probe Measurements in the 32 Wells at Vadose-Zone Test on May 10, 2001, After an Injection of 30,400 L of Hypersaline Water into (a) Transect E-A, (b) Transect F-B, (c) Transect C-G, and (d) Transect B-F

enhanced the lateral movement of water, resulting in water leaving the monitored domain via the southeastern quadrant (Figure 4.4), suggesting the importance of stratigraphy and lineation (strike and dip) of the depositional environment even for unsaturated flow processes. Effective anisotropy ratios (K_x:K_z) estimated from the deviation of the mean centroid trajectory from the direction of the mean head gradient ranged from 1 to 40. Inverse modeling with a saturation-dependent anisotropy model gave anisotropy ratios ranging from 4 to 25 for the major layers. Moisture content data were analyzed also by spatial moments and variogram modeling to determine the cause of asymmetry. Geostatistical analysis of the spatial correlation structure of moisture content showed significant anisotropy and a time dependence in the spatial continuity of moisture. The direction of maximum continuity was to the east, and correlation lengths were on the order of 100 m.

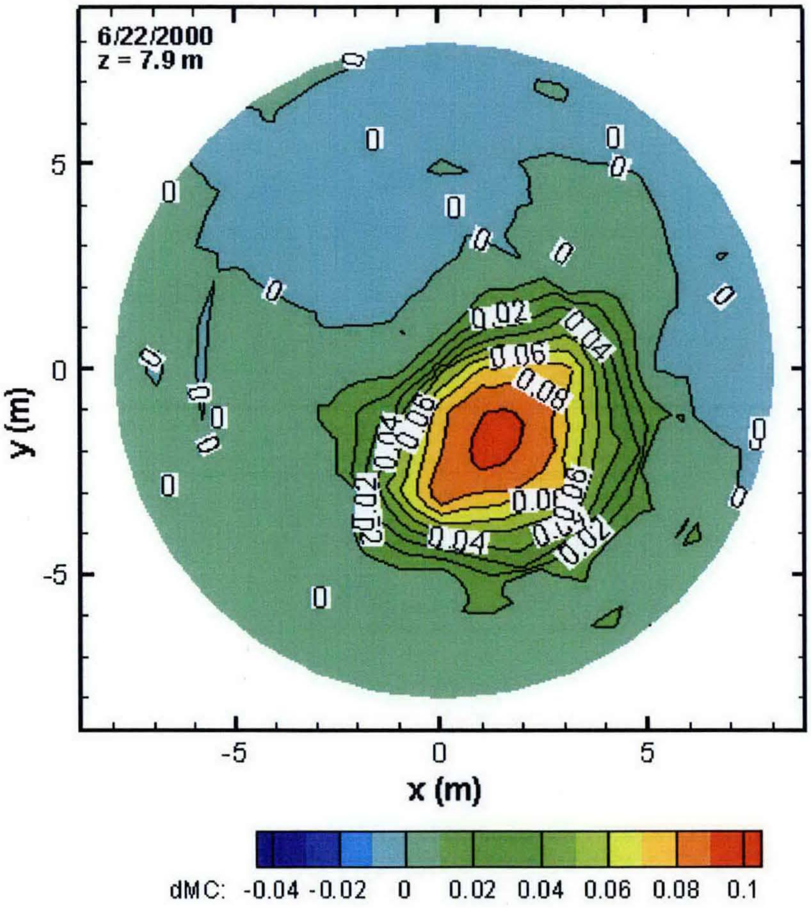


Figure 4.4. Plume Distribution at the Vertical Location of the Centroid after the Injection of 15,978 kg of Salt-Free Water at Coordinates 0,0. The movement of the plume was southeast. This plot represents the change in θ from the initial condition (after Ward et al. 2006a).

The importance of fine-scale lithologic variations to transport processes in the deep vadose zone emphasizes the need to consider layer sequence as well as the lineation when developing conceptual models of deep vadose zone transport. The concept of saturation-dependent anisotropy suggests that as the water content of a layered system decreases, the ratio of lateral to vertical flow increases. This phenomenon is not well understood for Hanford sediments.

4.4.2 Army Loop Road Clastic Dike Site

Two important requirements for accurate modeling of field-scale unsaturated transport using local-scale parameters are the development of methods to account for multiscale heterogeneity and the connectivity of the facies that control flow. Although the vertical correlation structure for the different waste sites is readily available from soil samples and numerous high-resolution borehole logs, little is known about the horizontal extent of the sedimentary facies and their properties that may control lateral movement. A series of experiments was conducted at the Army Loop Road Clastic Dike site to gain insight into the horizontal correlation structure of hydraulic properties and how flow and transport process may be affected by clastic dikes.

Infiltration experiments were conducted along a 60-m long transect at the Hanford Site using drip irrigation lines to create a line source (Ward and Gee 2003; Ward et al. 2006a). The transect was instrumented laterally at 1-m intervals at depths from the surface to 1 m to measure water content (θ), capillary pressure head (h), and tracer concentration. More than 16,644 L were applied to the surface over the duration of the experiment at a rate of about 243 L/day. Observations of water content and tracer concentrations were used to understand factors affecting subsurface distributions, to estimate field-scale transport parameters, and to quantify the spatial correlation structure of hydraulic and transport properties.

Hydraulic and air permeability measurements in dike materials showed permeabilities at least three orders of magnitude lower than in the coarse-textured sand host matrix (Murray et al. 2003, 2007). Of eight parameters assessed, the vertical saturated hydraulic conductivity, K_{sv}, was the most variable parameter, whereas the horizontal saturated hydraulic conductivity, K_{sh}, was the second most variable parameter. Parameter α, which is related to the soil entry pressure, showed an intermediate level of variability, whereas parameters n, θ_s, and the horizontal pore connectivity, L_h, had the smallest variability. Parameters K_{sh}, K_{sv}, α, and n were closer to a log-normal than to normal distributions, while θ_s and L_h were closer to normal distributions. The autocorrelation ranges of parameters K_{sh}, K_{sv}, α, and L_h in the horizontal direction were between 2.4 and 4.6 m. Parameters n and θ_s did not show any spatial autocorrelation. The spatial correlations between most of the parameter pairs were significant at the 95% or 99% level. There was evidence of saturation-dependent anisotropy; this can lead to an increased lateral spreading of contaminants parallel to layering. Ignoring anisotropy in flow simulations could result in poor predictions of the magnitude and direction of flow and contaminant movement. The inversely estimated parameters show that, in general, the anisotropy in K at the test site increases with decreasing saturation. In an anisotropic soil, the direction of the hydraulic gradient and that of the flow are different. Generally, the flow direction tends to conform to the direction, with larger conductivity if the direction of the gradient is not parallel to the principal direction. Changes in the dominant direction of K_{sh} and K_{sv} were observed at this site, and the enhanced soil anisotropy at low saturation had a significant impact on flow direction. For a soil with saturation-dependent anisotropy, even when the direction of hydraulic gradient does not change, the flow direction will vary with saturation. These phenomena were well described with a tensorial connectivity–tortuosity model, but there is limited information on the required model parameters for deep vadose zone materials.

4.5 Activity Outcomes Required To Fill Data Gaps

Successful implementation of surface barriers for deep vadose zone contaminants requires that data gaps be identified and addressed. This section identifies the data gaps that currently hinder deployment of surface barriers for deep vadose zone contaminants, and it identifies a set of activity outcomes that will address those data gaps.

4.5.1 Data Gaps

Success in using surface barriers to protect groundwater from deep vadose zone contamination is constrained by a number of factors, some of which are mentioned in the strategy element discussion. To facilitate understanding, the constraining factors have been grouped into four high-level data gaps:

1. **Limited access**. The deep vadose zone is difficult and costly to access because of the increased depth and the potential for drilling through contaminated zones.
2. **Limited data**. Because of the limited access, there is a severe lack of information on the lateral and vertical extent of contamination and the spatial distribution of concentrations and water contents. Also lacking are observations of the long-term behavior of contaminants in the deep vadose zone.
3. **Limited time**. Most contaminants are expected to be moving at rates so low that movement might not be detectable for anywhere from 10 to more than 100 years.
4. **Lack of accepted predictive capability**. Although models have been used for various purposes, confidence in their ability to predict the influence of surface barriers on contaminant migration in the deep vadose zone is limited.

These gaps are consistent with those identified by Looney and Falta (2000).

4.5.2 Required Outcomes

To address the data gaps identified above, four outcomes were identified. Each is discussed briefly below.

Common Evaluation Methodology. Although many modeling studies of various issues have been performed, there is no clear, consistent, and defensible approach. Such an approach is necessary to public acceptance, given the limited access to the deep vadose zone and the potential for complex remediation activities. What would be valuable for DOE to have is a common evaluation methodology that provides a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above deep vadose zone contamination.

Deep Vadose Zone Data. A common concern of any cleanup activity is lack of sufficient data to adequately characterize the subsurface, the contaminant plumes, and the results of any remediation activities. This concern is amplified for the deep vadose zone given the physical challenges and cost of access. Thus, an important outcome of activities to address the data gaps listed above will the provision of deep vadose zone data that characterize the lithology, the spatial distribution of moisture and contaminants, and the impacts to the contaminants following placement of a surface barrier.

Subsurface Monitoring. Geophysical techniques have been developed predominantly for near-surface remediation, primarily because many of the contamination problems are shallow and access is easy. However, it is not clear which of the geophysical techniques are effective and applicable at deeper depths. Thus, subsurface monitoring technologies are required that can access the deep vadose zone for both characterization and monitoring. These technologies must be able to resolve subtle changes that may occur during the many years to decades following treatment and closure.

Field Observations. The remediation options for the deep vadose zone will require many years to implement and observe results. Decisions have to be made much sooner, so a model-based evaluation methodology will have to be employed. The credibility of the methodology depends on how accurate the predictions are, which can be determined only by conducting multiple rigorous tests of the modeling tools using field observations. Thus, field observations that span years to decades are required to test the evaluation methodology.

These outcomes are consistent with the recommendations provided by Looney and Falta (2000). Tasks focused on these outcomes will provide the technical basis for credible and robust surface barrier evaluations for deep vadose zone contaminants.

5.0 Proposed Tasks to Support Evaluation of Surface Barriers for the Deep Vadose Zone

A key objective identified for the deep vadose zone is to provide a defensible methodology with which to evaluate the groundwater impacts afforded by placement of a surface barrier above deep vadose zone contamination. Section 4 identified gaps in the knowledge base for this type of methodology and identified a set of activity outcomes that would fill those gaps. Achieving those outcomes will increase the likelihood of successful implementation of surface barriers for deep vadose zone sites. Tasks designed to achieve those outcomes will require an investment of time and resources. To keep those tasks focused, four outcomes were identified:

- *common evaluation methodology* that provides a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above deep vadose zone contamination
- *deep vadose zone data* that characterizes the lithology, the spatial distribution of moisture and contaminants, and the impacts to the contaminants following placement of a surface barrier
- *subsurface monitoring* technologies to access the subsurface for characterization and monitoring and resolve subtle changes during multiyear periods
- *field observations* that span years to decades to test the evaluation methodology.

This section identifies a set of tasks designed to provide the information needed to satisfy these outcomes.

5.1 Evaluation Methodology

Objective: Develop common evaluation methodology to predict groundwater impacts due to placement of a surface barrier.

Existing studies of vadose zone contamination have been guided by project-specific schedules and objectives, but there is no overarching evaluation process that is sensitive to deep vadose zone concerns and issues and provides consistency among the studies. Furthermore, no process exists that defensibly addresses all elements: the science, the complexity, and the impacts of remediation activities. This task will provide a clear, consistent, and defensible basis for evaluating groundwater impacts caused by placement of a surface barrier above deep vadose zone contamination.

Scope: The methodology developed by this task will address the issues identified in Section 3, including heterogeneity, anisotropy, barrier size, increased recharge under barrier side slopes, alternative lithologic and hydrologic conceptual site models, contaminant depth below the surface barrier, and remediation activities (e.g., in situ gas-phase treatment of the contaminants; desiccation). The methodology will also address evaluation issues such as optimal boundary conditions, gridding, dimensionality, and metrics. Although the STOMP computer code has been the predominant code applied to date at Hanford, the methodology will be applicable using any simulation code with similar capabilities.

Schedule: TBD.

Outcome: This task will produce a common evaluation methodology (containing guidance and input files) for evaluating groundwater impacts that can provide feedback to the surface barrier design criteria and guide vadose zone monitoring decisions regarding technologies, placement, and analysis of monitoring results. The methodology will be published and made available online to promote transfer of knowledge and ensure commonality of results.

5.2 Case Studies

Objective: Conduct case studies to demonstrate the applicability of the common evaluation methodology. Three sites expected to have conditions that would yield valuable information and experience pertinent to deep vadose zone contamination were chosen to cover a range of conditions. The sites, conditions, and reasons for being chosen are

- BC cribs and trenches – The site has a fine sand soil surface and sparse plants; recharge is expected to be low. The primary contaminant of interest is technetium, which is mobile. Ongoing characterization and remediation activities at the site provide a set of data with which to demonstrate the methodology.
- U Plant cribs – The site has a coarse sand to gravel surface and sparse plants along the periphery of the cribs; recharge is expected to be high. The primary contaminant of interest is uranium, which sorbs somewhat to the sediments. Recent characterization and remediation activities at the site provide a set of data with which to demonstrate the methodology. In addition, a surface barrier is being considered for deployment at this site in the next few years.
- T Farm interim cover – The site has a sandy gravel surface and no plants; recharge is expected to be high. The contaminant of interest is technetium, which is mobile. Recent characterization and monitoring activities associated with the interim cover deployment at the site provide a set of data with which to demonstrate the methodology.

Scope: The case studies will demonstrate the methodology using existing site-specific data to illustrate impacts. The case studies will be demonstrations of the evaluation methodology; they will not be complete and exhaustive site-specific evaluations.

Schedule: TBD.

Outcome: This task will publish the results of the three case studies along with the associated input files. The results will demonstrate the evaluation methodology and provide a preliminary view of the value of placing a surface barrier.

5.3 Subsurface Monitoring Technologies

Objective: Evaluate minimally invasive geophysical approaches for delineating subsurface plumes and monitoring their migration in the deep vadose zone.

The development and application of geophysics technology at Hanford has generally been focused to date on detecting and monitoring relatively shallow contamination, typically in the upper 15–20 m of the vadose zone. To detect and monitor deeper contamination will require reconsideration of the existing techniques and tools to overcome the limitations of far fewer access points and far greater uncertainty (e.g., contaminant plume dimensions, geologic heterogeneity).

Scope: Integrate appropriate hydrologic methods (e.g., neutron probe, capacitance probe) and geophysical methods (e.g., electrical resistivity, self potential, dielectric permittivity) for the design of a dynamical long-term monitoring system capable of delineating subsurface plumes and monitoring their migration. Focus on using existing infrastructure (well casings), coupled with surface electrodes and isolated deep electrodes (as may be installed at the bottom of a well completion) as part of a monitoring network. Establish data quality objectives, identify spatial and temporal monitoring requirements, and optimize electrode spacing. Integrate monitoring with modeling as a means of improving the conceptual model.

Schedule: TBD.

Outcome: This task will produce an autonomous dynamical geophysical monitoring system that complements hydrogeological methods of site characterization and monitoring to provide higher spatial and temporal resolution. Results will be summarized in a document that identifies optimal acquisition geometries and establishes correlations between geophysical attributes and plume characteristics.

5.4 Controlled Field Test at Sisson and Lu Site

Objective: Evaluate the ability of the model to predict long-term liquid, vapor, and chemical transport processes at a well-characterized site containing a plume of subsurface water and tracer remaining from injections in the early 1980s and 2000s.

The previous tests conducted at the Sisson and Lu site in the 200 East Area include the injection of well-defined quantities of water and tracers. More than 6 years have passed and the question to be answered is whether the plume that resulted from that testing can be detected with current characterization and monitoring technologies. Just as important is to determine how much the plume may have moved laterally. The resulting set of data will be ideal for testing the ability of the evaluation methodology.

Scope: Supplement existing instrumentation with sensors to measure hydrologic variables including water potential, water content, relative humidity, temperature, and electrical resistivity. Analyze sediment samples collected during instrumentation to quantify naturally occurring tracers, including chloride (Cl^-) and the isotopes of hydrogen and/or oxygen that become part of the water molecule (e.g., as $HD^{16}O$ and $H_2{}^{18}O$). Use resulting data to test a multiphase, nonisothermal model that can compute simultaneous movement of liquid, vapor, and heat, with multiphase, multicomponent transport.

Schedule: TBD.

Outcomes: This task will produce a calibrated and verified, field-tested, transient flow and transport model that predicts the simultaneous movement of liquid, vapor, and heat, with multiphase, multicomponent transport. Publication will demonstrate the ability of the method to predict field observations of liquid, vapor, and chemical movement, analyze conceptual model and parameter sensitivity, and compare the utility of different subsurface monitoring methods.

5.5 Deep Vadose Zone Monitoring at T Farm

Objective: Demonstrate the ability of the geophysical sensors and the model to detect and predict long-term migration of liquid and vapor between the vadose zone beneath the infiltration area and the vadose zone protected by the interim cover.

The ongoing infiltration of runoff water north of the site provides a unique opportunity to observe, within a few years, a large plume of water migrating through the vadose zone. Successful detection, monitoring, and prediction of that plume will be invaluable to establishing credibility in the monitoring technology and prediction methodology.

Scope: The infiltration area north of T Farm should provide a huge signal in the vadose zone and may present the best opportunity for detecting significant lateral spreading. The existing monitoring network will be supplemented with geophysics sensors that overlap the network (to calibrate) and encompass the vadose zone between the infiltration area and the interim cover. This task will be conducted in coordination with the existing T Farm interim cover monitoring project and will not impact their operations.

Schedule: TBD.

Outcome: This task will produce vadose zone data, field observations, and model predictions of the vadose zone changes that have occurred during since placement of the interim cover in 2008. Because the water plume beneath the infiltration area is expected to alter the vadose zone hydrologic conditions quickly and significantly, the expectation is that water content changes should be detectable within a few years. In addition, this test provides an excellent test of the potential for lateral movement from a high recharge zone to the vadose zone beneath a surface barrier. Publication will include the vadose zone data, field observations, model predictions, and an evaluation of the ability to measure and predict lateral water movement associated with an infiltration area located adjacent to a surface barrier.

5.6 Deep Vadose Zone Monitoring at Prototype Hanford Barrier

Objective: Demonstrate the ability of geophysical sensors and the model to detect and predict the hydrologic conditions in the vadose zone beneath the PHB 15 years after construction.

The PHB is the only long-term surface barrier design deployed at Hanford. The barrier is extensively instrumented to monitor near-surface conditions, and it includes some monitoring technology just beneath (within 3 m of) the bottom of the barrier. In addition, the barrier includes two side slope designs that are partially monitored. The full-scale nature of this barrier, the extensive monitoring data set, and the 15-year record all make this a unique opportunity to quantify what changes have occurred in the vadose zone beneath the barrier and the side slopes and to determine whether the evaluation methodology can reproduce the observations.

Scope: Install geophysics sensors beneath the PHB to characterize the hydrologic conditions beneath the central portion of the barrier, beneath the side slopes, and beyond the side slopes (e.g., BY tank farm). Determine the depth and lateral extent of protectiveness of the surface barrier. A key element of this task is to install instruments and monitor deeper than the current PHB monitoring systems.

Schedule: TBD.

Outcome: This task will produce vadose zone data, field observations, and model predictions of the vadose zone changes that have occurred during the 15 years since emplacement of the PHB. Publication will include the vadose zone data, field observations, model predictions, and an evaluation of the ability to measure and predict vadose zone processes associated with a field-scale surface barrier.

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